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Atherton et al.

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(54) **PCI-E REAL-TIME FLOW CONTROL OPTIMIZATION**

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G06F 13/40	(2006.01)
G06F 13/374	(2006.01)

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(58) **Field of Classification Search**

CPC H04W 28/10; G06F 8/433

See application file for complete search history.

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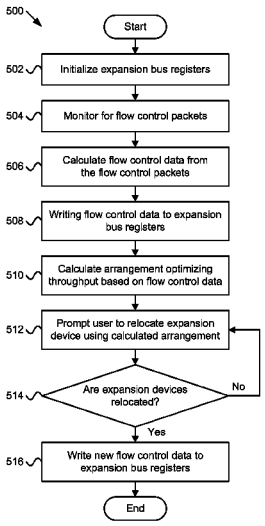
(74) *Attorney, Agent, or Firm* — Kunzler, PC

(57) **ABSTRACT**

For optimizing expansion devices on a computer expansion bus based on real-time flow control data, a system, apparatus, method, and computer program product are disclosed. The apparatus includes a configuration module that initializes a plurality of expansion bus registers, each expansion bus register associated with one of the plurality of expansion bus slots, a packet module that monitors flow control packets on the expansion bus, a flow control module that calculates flow control data from the flow control packets, the flow control data relating to the plurality of expansion devices, and a register module that writes flow control data to the plurality of expansion bus registers. The apparatus may further includes an optimization module that calculates an arrangement of the plurality of expansion devices, based on the flow control data, to maximize expansion bus throughput.

20 Claims, 7 Drawing Sheets



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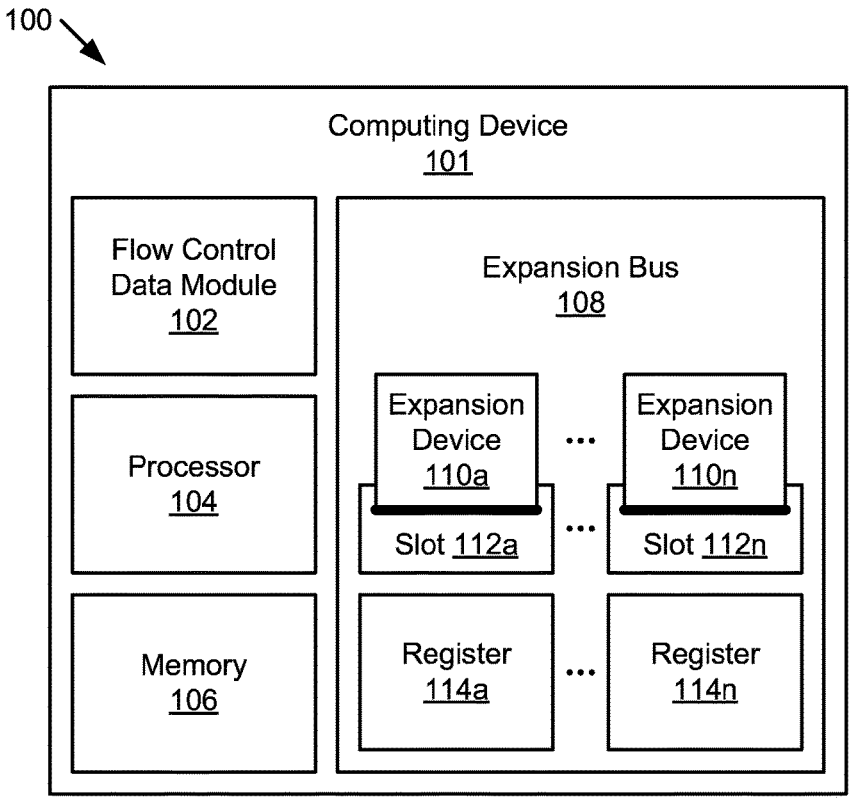
100
Computing Device
101
Flow Control
Data Module
102
Expansion Bus
108
Expansion
Device
110a
Expansion
Device
110n
Processor
104
Slot 112a
Slot 112n
Memory
106
Register
114a
Register
114n

FIG. 1

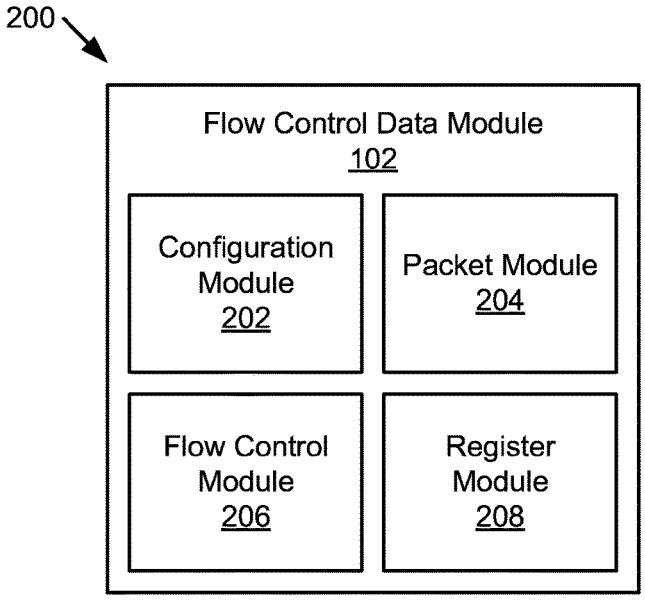
200
Flow Control Data Module
102
Configuration
Module
202
Packet Module
204
Flow Control
Module
206
Register
Module
208

FIG. 2

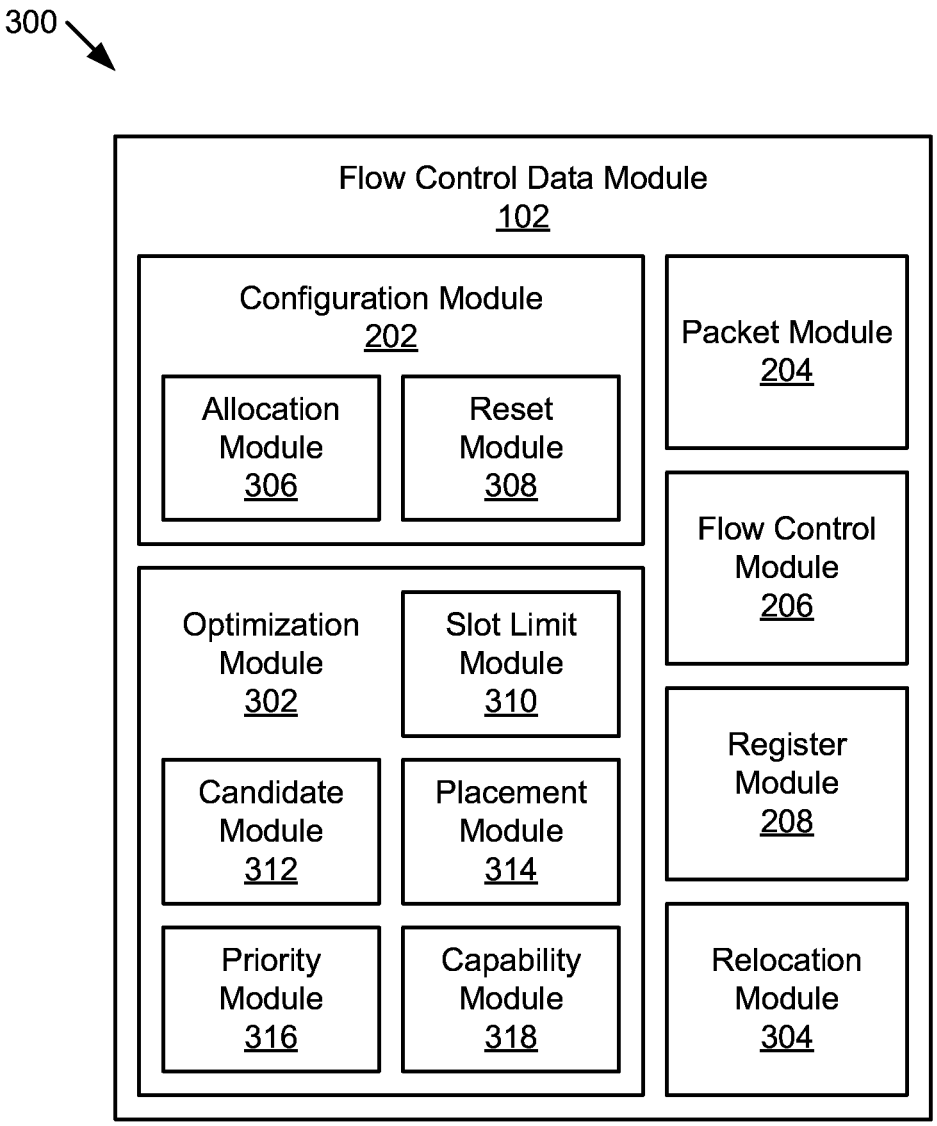
300
Flow Control Data Module
102
Configuration Module
202
Allocation Module
306
Reset Module
308
Optimization Module
302
Slot Limit Module
310
Candidate Module
312
Placement Module
314
Priority Module
316
Capability Module
318
Packet Module
204
Flow Control Module
206
Register Module
208
Relocation Module
304

FIG. 3

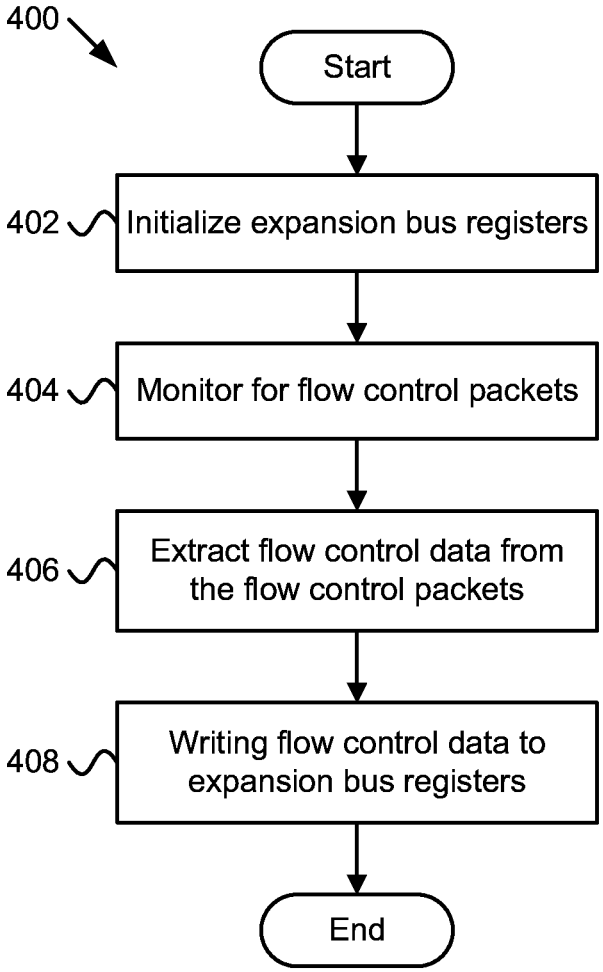
400
Start
402
Initialize expansion bus registers
404
Monitor for flow control packets
406
Extract flow control data from the flow control packets
408
Writing flow control data to expansion bus registers
End

FIG. 4

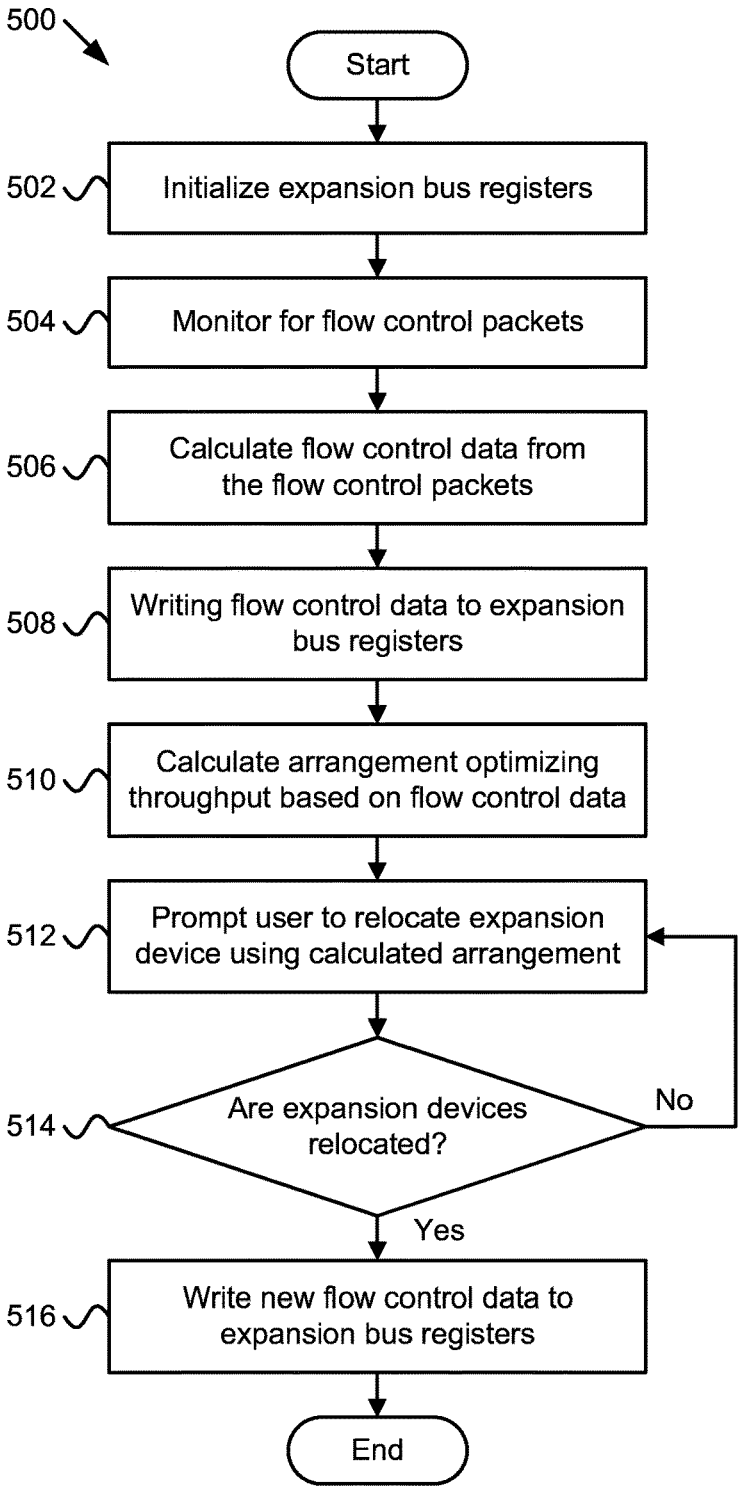
500
Start
502
Initialize expansion bus registers
504
Monitor for flow control packets
506
Calculate flow control data from the flow control packets
508
Writing flow control data to expansion bus registers
510
Calculate arrangement optimizing throughput based on flow control data
512
Prompt user to relocate expansion device using calculated arrangement
514
Are expansion devices relocated?
No
Yes
516
Write new flow control data to expansion bus registers
End

FIG. 5

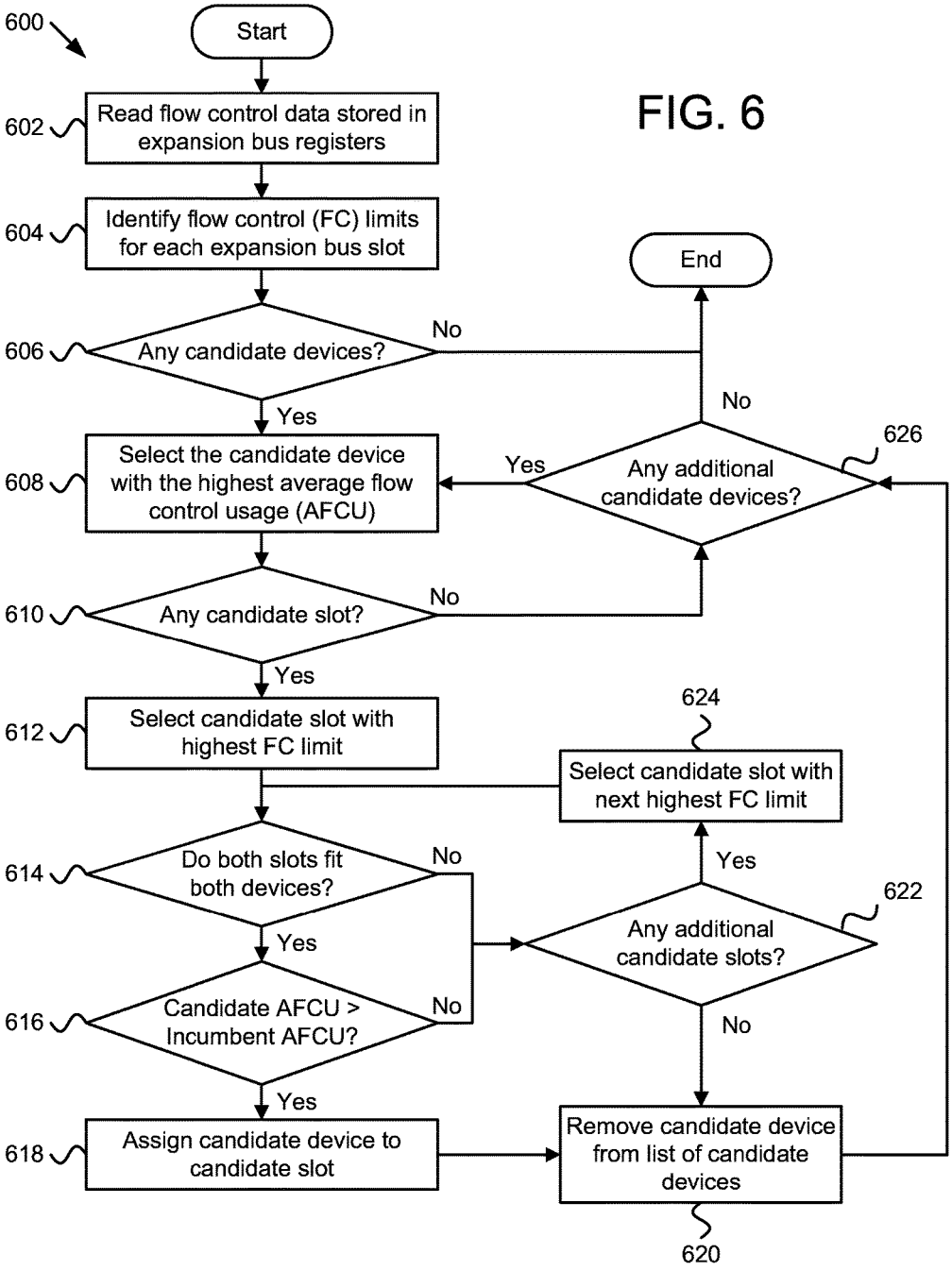
600
Start
602
Read flow control data stored in expansion bus registers
604
Identify flow control (FC) limits for each expansion bus slot
606
Any candidate devices?
No
End
Yes
608
Select the candidate device with the highest average flow control usage (AFCU)
Yes
626
Any additional candidate devices?
No
610
Any candidate slot?
No
Yes
612
Select candidate slot with highest FC limit
624
Select candidate slot with next highest FC limit
614
Do both slots fit both devices?
No
Yes
622
Any additional candidate slots?
Yes
616
Candidate AFCU > Incumbent AFCU?
No
No
Yes
618
Assign candidate device to candidate slot
Remove candidate device from list of candidate devices
620

FIG. 6

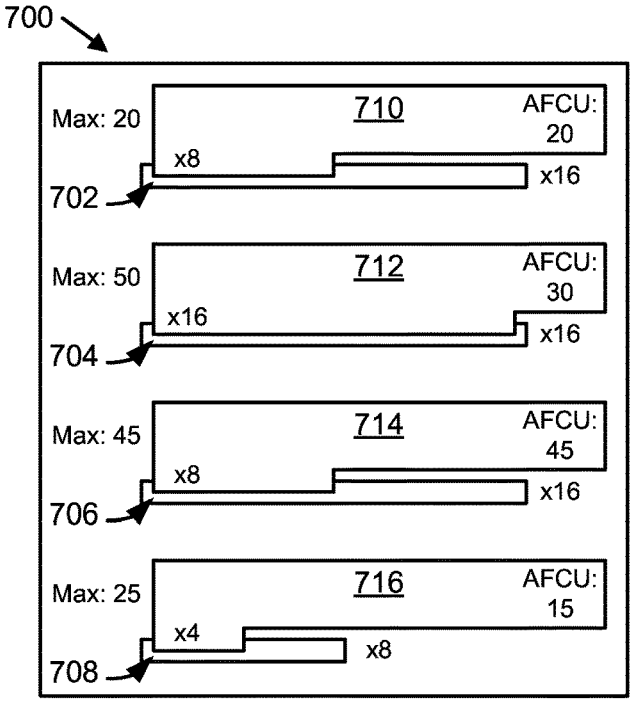
700
Max: 20
710
AFCU: 20
x8
x16
702
Max: 50
712
AFCU: 30
x16
x16
704
Max: 45
714
AFCU: 45
x8
x16
706
Max: 25
716
AFCU: 15
x4
x8
708

FIG. 7A

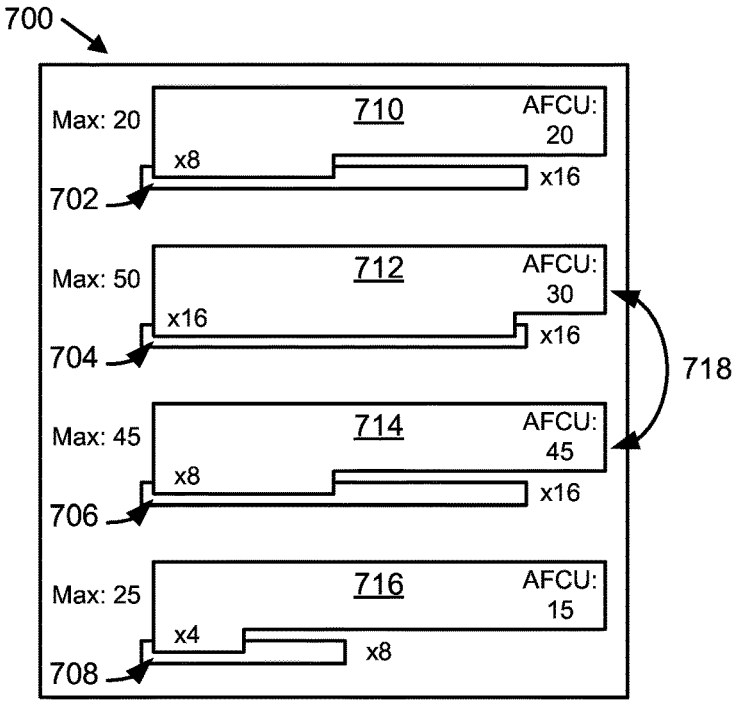
700
Max: 20
710
AFCU: 20
x8
x16
702
Max: 50
712
AFCU: 30
x16
x16
704
718
Max: 45
714
AFCU: 45
x8
x16
706
Max: 25
716
AFCU: 15
x4
x8
708

FIG. 7B

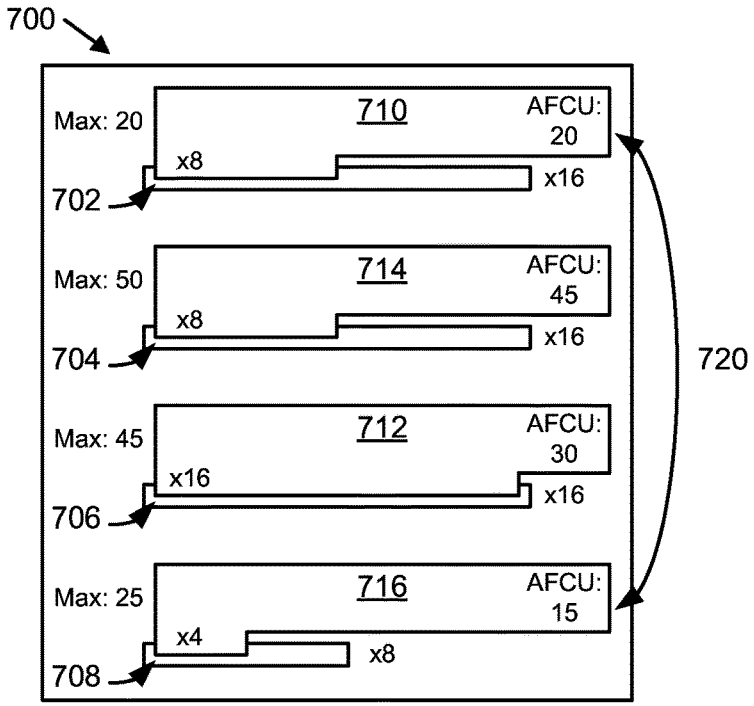
700
Max: 20
710
AFCU: 20
x8
x16
702
Max: 50
714
AFCU: 45
x8
x16
704
Max: 45
712
AFCU: 30
x16
x16
706
Max: 25
716
AFCU: 15
x4
x8
708
720

FIG. 7C

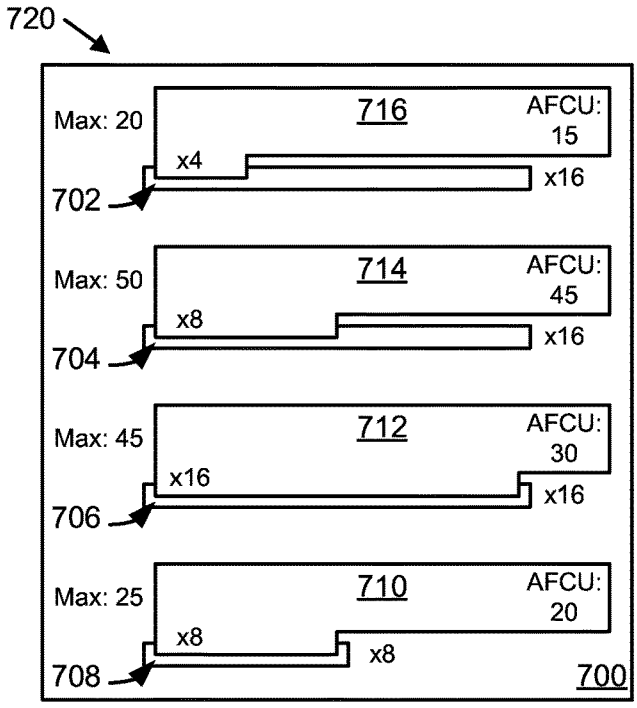
720
Max: 20
716
AFCU: 15
x4
x16
702
Max: 50
714
AFCU: 45
x8
x16
704
Max: 45
712
AFCU: 30
x16
x16
706
Max: 25
710
AFCU: 20
x8
x8
708
700

FIG. 7D

PCI-E REAL-TIME FLOW CONTROL OPTIMIZATION

FIELD

The subject matter disclosed herein relates to computer expansion buses and more particularly relates to optimizing expansion devices on a computer expansion bus based on real-time flow control data.

BACKGROUND

Description of the Related Art

Expansion busses allow for added functionality of a computer system. Data transfer on an expansion bus is governed, in part, by flow control, such as data transfer based on available flow control credits. However, a user cannot easily determine whether the computer system is in an optimized configuration which can result in computer systems where the flow control and credits are not optimized for the computer system.

BRIEF SUMMARY

An apparatus for optimizing expansion devices on a computer expansion bus based on real-time flow control data is disclosed. A method and computer program product also perform the functions of the apparatus.

The apparatus includes a configuration module that initializes a plurality of expansion bus registers. Each expansion bus register is associated with one of the plurality of expansion bus slots. The apparatus includes a packet module that monitors flow control packets on the expansion bus, and a flow control module that calculates flow control data from the flow control packets. The flow control data relates to the plurality of expansion devices. The apparatus includes a register module that writes flow control data to the plurality of expansion bus registers.

In some embodiments, the apparatus further includes an optimization module that calculates an arrangement of the plurality of expansion devices to maximize expansion bus throughput. The arrangement is calculated based on the flow control data. The apparatus may include a relocation module that prompts a user to relocate at least one of the plurality of expansion devices into a different expansion bus slot. The apparatus may include a reset module that deletes data values stored in the plurality of expansion bus registers in response to the at least one expansion device being relocated. The register module writes new flow control data to the plurality of expansion bus registers based on the relocated expansion device in response to the at least one expansion device being relocated.

In certain embodiments, the optimization module includes a slot limit module that identifies flow control limits for each of the plurality of expansion bus slots. The optimization module includes a candidate module that compares, for each of the plurality of expansion bus slots, an average flow control usage for an expansion device using the expansion bus slot to an identified flow control limit for the expansion bus slot. The flow control data includes average flow control usage for each of the plurality of expansion devices. The candidate module selects at least one candidate expansion device from the plurality of expansion devices based on the comparison. The optimization module includes a placement module that assigns each candidate expansion device to one of the plurality of expansion bus slots based on the average flow control usage and the flow control limits.

In some embodiments, the apparatus includes a priority module that ranks the at least one candidate expansion device based on highest average flow control usage. The apparatus may include a compatibility module that compares a physical size of an expansion device to a size supported by an expansion bus slot. The placement module assigns each candidate expansion device to one of the plurality of expansion bus slots based on the size comparison.

In certain embodiments, the configuration module includes an allocation module that identifies an unused expansion bus register for each expansion bus slot and allocates the identified expansion bus registers for storing flow control data. The configuration module also includes a reset module that deletes data values stored in the allocated expansion bus registers. In some embodiments, the plurality of expansion bus registers further includes a plurality of extended capability registers for a peripheral component interconnect express (PCIe) expansion bus. Each extended capability register stores flow control data of one of plurality of expansion bus slots.

In some embodiments, the flow control data includes average flow control usage for each expansion device, a ratio of average flow control usage to flow control limit for each expansion device, and/or an average amount of unused flow control credits for each expansion device. In certain embodiments, the register module further updates the flow control data stored to the plurality of expansion bus registers in response to the flow control module calculating additional flow control data.

The method includes initializing a plurality of expansion bus registers. Each expansion bus register is associated with one of a plurality of expansion bus slots. The method includes monitoring for flow control packets on an expansion bus. The method includes extracting flow control data from the flow control packets. The method includes the flow control data relating to a plurality of expansion devices operating on the expansion bus. The method includes writing flow control data to the plurality of expansion bus registers based on the flow control packets.

In some embodiments, the method includes calculating an arrangement of the plurality of expansion devices that optimizes throughput based on the flow control data. Each of the plurality of expansion devices is coupled to one of the plurality of expansion bus slot. In certain embodiments, the method includes prompting a user to relocate at least one of the plurality of expansion devices into a different expansion bus slot based on the calculated arrangement. The method may include determining that the at least one expansion device is relocated. The method may include resetting the plurality of expansion bus registers storing flow control data. The method may include writing new flow control data to the plurality of expansion bus registers based on the relocated expansion device.

In some embodiments, optimizing throughput of the plurality of expansion devices based on the flow control data includes identifying flow control limits for each of the plurality of expansion bus slots. Optimizing throughput includes, for each of the plurality of expansion bus slots, comparing an average flow control usage for an expansion device using the expansion bus slot to an identified flow control limit for the expansion bus slot. The flow control data includes average flow control usage for each of the plurality of expansion devices.

The method may also include determining at least one candidate expansion device from the plurality of expansion

devices based on the comparison. The method may include assigning each candidate expansion device to one of the plurality of expansion bus slots based on the average flow control usage and the flow control limits. In certain embodiments, the method also includes assigning a priority to each candidate expansion device based on average flow control usage. The candidate expansion device having the highest average flow control usage is assigned a highest priority. Assigning each candidate expansion device to one of the plurality of expansion bus slots is further based on the priority of each candidate expansion device.

In some embodiments, assigning a candidate expansion device to one of the plurality of expansion bus slots includes selecting a candidate expansion device having the highest average flow control usage. The selected candidate expansion device is coupled to an incumbent expansion bus slot. Assigning the candidate expansion device to one of the plurality of expansion bus slots includes determining at least one candidate expansion bus slot from the plurality of expansion bus slots. Each candidate expansion bus slot is physically compatible with the selected candidate expansion device and has a flow control limit larger than the average flow control usage of the selected candidate expansion device.

Assigning the candidate expansion device to one of the plurality of expansion bus slots includes selecting a candidate expansion bus slot having a highest flow control limit. The selected candidate expansion bus slot is coupled to an incumbent expansion device. Assigning the candidate expansion device to one of the plurality of expansion bus slots may include determining that the incumbent expansion device is physically compatible with the incumbent expansion bus slot. Assigning the candidate expansion device to one of the plurality of expansion bus slots may include determining that the average flow control usage of the incumbent expansion device is less than or equal to the average flow control usage of the candidate expansion device.

In some embodiments, initializing the plurality of expansion bus registers includes allocating an extended capability register for each expansion bus slot for storing flow control data. In certain embodiments, initializing the plurality of expansion bus registers further includes identifying an unused expansion bus register for each expansion bus slot. Initializing the plurality of expansion bus registers includes allocating the identified registers for storing flow control data. Initializing the plurality of expansion bus registers includes resetting data values stored in the allocated expansion bus registers.

In some embodiments, extracting flow control data from the flow control packets includes calculating a number of available flow control credits. In some embodiments, writing flow control data to the plurality of expansion bus registers includes, for each of the plurality of expansion bus slots, storing an average flow control usage for an expansion device associated with the expansion bus slot.

The computer program product includes a computer readable storage medium that stores code executable by a processor, the executable code including code to initialize a plurality of expansion bus registers. Each expansion bus register is associated with one of a plurality of expansion bus slots. The executable code includes code to detect flow control packets on an expansion bus. The executable code includes code to calculate flow control data from the flow control packets. The flow control data relates to a plurality of expansion devices operating on the expansion bus. The executable code includes code to store flow control data to the plurality of expansion bus registers based on the flow control packets.

BRIEF DESCRIPTION OF THE DRAWINGS

A more particular description of the embodiments briefly described above will be rendered by reference to specific embodiments that are illustrated in the appended drawings. Understanding that these drawings depict only some embodiments and are not therefore to be considered to be limiting of scope, the embodiments will be described and explained with additional specificity and detail through the use of the accompanying drawings, in which:

FIG. **1** is a schematic block diagram illustrating one embodiment of a computer system for optimizing expansion devices on a computer expansion bus based on real-time flow control data;

FIG. **2** is a schematic block diagram illustrating one embodiment of an apparatus for optimizing expansion devices on a computer expansion bus based on real-time flow control data;

FIG. **3** is a schematic block diagram illustrating another embodiment of an apparatus for optimizing expansion devices on a computer expansion bus based on real-time flow control data;

FIG. **4** is a schematic flow chart diagram illustrating one embodiment of a method for optimizing expansion devices on a computer expansion bus based on real-time flow control data;

FIG. **5** is a schematic flow chart diagram illustrating another embodiment of a method for optimizing expansion devices on a computer expansion bus based on real-time flow control data;

FIG. **6** is a schematic flow chart diagram illustrating one embodiment of a method for calculating an arrangement of the plurality of expansion devices that optimizes throughput based on the flow control data;

FIG. **7**A is a diagram illustrating one embodiment of optimizing expansion devices on a computer expansion bus based on real-time flow control data; and

FIG. **7**B is a diagram illustrating a first step of optimizing expansion devices on a computer expansion bus based on real-time flow control data;

FIG. **7**C is a diagram illustrating a second step of optimizing expansion devices on a computer expansion bus based on real-time flow control data; and

FIG. **7**D is a diagram illustrating an embodiment of an arrangement of the plurality of expansion devices that optimizes throughput based on the flow control data.

DETAILED DESCRIPTION

As will be appreciated by one skilled in the art, aspects of the embodiments may be embodied as a system, method, or program product. Accordingly, embodiments may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.) or an embodiment combining software and hardware aspects that may all generally be referred to herein as a "circuit," "module" or "system." Furthermore, embodiments may take the form of a program product embodied in one or more computer readable storage devices storing machine readable code, computer readable code, and/or program code, referred hereafter as code. The storage devices may be tangible, non-transitory, and/or non-trans-

mission. The storage devices may not embody signals. In a certain embodiment, the storage devices only employ signals for accessing code.

Many of the functional units described in this specification have been labeled as modules, in order to more particularly emphasize their implementation independence. For example, a module may be implemented as a hardware circuit comprising custom VLSI circuits or gate arrays, off-the-shelf semiconductors such as logic chips, transistors, or other discrete components. A module may also be implemented in programmable hardware devices such as field programmable gate arrays, programmable array logic, programmable logic devices, or the like.

Modules may also be implemented in code and/or software for execution by various types of processors. An identified module of code may, for instance, comprise one or more physical or logical blocks of executable code which may, for instance, be organized as an object, procedure, or function. Nevertheless, the executables of an identified module need not be physically located together, but may comprise disparate instructions stored in different locations which, when joined logically together, comprise the module and achieve the stated purpose for the module.

Indeed, a module of code may be a single instruction, or many instructions, and may even be distributed over several different code segments, among different programs, and across several memory devices. Similarly, operational data may be identified and illustrated herein within modules, and may be embodied in any suitable form and organized within any suitable type of data structure. The operational data may be collected as a single data set, or may be distributed over different locations including over different computer readable storage devices. Where a module or portions of a module are implemented in software, the software portions are stored on one or more computer readable storage devices.

Any combination of one or more computer readable medium may be utilized. The computer readable medium may be a computer readable storage medium. The computer readable storage medium may be a storage device storing the code. The storage device may be, for example, but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, holographic, micromechanical, or semiconductor system, apparatus, or device, or any suitable combination of the foregoing.

More specific examples (a non-exhaustive list) of the storage device would include the following: an electrical connection having one or more wires, a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a portable compact disc read-only memory (CD-ROM), an optical storage device, a magnetic storage device, or any suitable combination of the foregoing. In the context of this document, a computer readable storage medium may be any tangible medium that can contain, or store a program for use by or in connection with an instruction execution system, apparatus, or device.

Code for carrying out operations for embodiments may be written in any combination of one or more programming languages including an object oriented programming language such as Python, Ruby, Java, Smalltalk, C++, or the like, and conventional procedural programming languages, such as the "C" programming language, or the like, and/or machine languages such as assembly languages. The code may execute entirely on the user's computer, partly on the user's computer, as a stand-alone software package, partly on the user's computer and partly on a remote computer or entirely on the remote computer or server. In the latter scenario, the remote computer may be connected to the user's computer through any type of network, including a local area network (LAN) or a wide area network (WAN), or the connection may be made to an external computer (for example, through the Internet using an Internet Service Provider).

Reference throughout this specification to "one embodiment," "an embodiment," or similar language means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, appearances of the phrases "in one embodiment," "in an embodiment," and similar language throughout this specification may, but do not necessarily, all refer to the same embodiment, but mean "one or more but not all embodiments" unless expressly specified otherwise. The terms "including," "comprising," "having," and variations thereof mean "including but not limited to," unless expressly specified otherwise. An enumerated listing of items does not imply that any or all of the items are mutually exclusive, unless expressly specified otherwise. The terms "a," "an," and "the" also refer to "one or more" unless expressly specified otherwise.

Furthermore, the described features, structures, or characteristics of the embodiments may be combined in any suitable manner. In the following description, numerous specific details are provided, such as examples of programming, software modules, user selections, network transactions, database queries, database structures, hardware modules, hardware circuits, hardware chips, etc., to provide a thorough understanding of embodiments. One skilled in the relevant art will recognize, however, that embodiments may be practiced without one or more of the specific details, or with other methods, components, materials, and so forth. In other instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of an embodiment.

Aspects of the embodiments are described below with reference to schematic flowchart diagrams and/or schematic block diagrams of methods, apparatuses, systems, and program products according to embodiments. It will be understood that each block of the schematic flowchart diagrams and/or schematic block diagrams, and combinations of blocks in the schematic flowchart diagrams and/or schematic block diagrams, can be implemented by code. These code may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a machine, such that the instructions, which execute via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts specified in the schematic flowchart diagrams and/or schematic block diagrams block or blocks.

The code may also be stored in a storage device that can direct a computer, other programmable data processing apparatus, or other devices to function in a particular manner, such that the instructions stored in the storage device produce an article of manufacture including instructions which implement the function/act specified in the schematic flowchart diagrams and/or schematic block diagrams block or blocks.

The code may also be loaded onto a computer, other programmable data processing apparatus, or other devices to cause a series of operational steps to be performed on the computer, other programmable apparatus or other devices to produce a computer implemented process such that the code

which execute on the computer or other programmable apparatus provide processes for implementing the functions/acts specified in the flowchart and/or block diagram block or blocks.

The schematic flowchart diagrams and/or schematic block diagrams in the Figures illustrate the architecture, functionality, and operation of possible implementations of apparatuses, systems, methods, and program products according to various embodiments. In this regard, each block in the schematic flowchart diagrams and/or schematic block diagrams may represent a module, segment, or portion of code, which comprises one or more executable instructions of the code for implementing the specified logical function(s).

It should also be noted that, in some alternative implementations, the functions noted in the block may occur out of the order noted in the Figures. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. Other steps and methods may be conceived that are equivalent in function, logic, or effect to one or more blocks, or portions thereof, of the illustrated Figures.

Although various arrow types and line types may be employed in the flowchart and/or block diagrams, they are understood not to limit the scope of the corresponding embodiments. Indeed, some arrows or other connectors may be used to indicate only the logical flow of the depicted embodiment. For instance, an arrow may indicate a waiting or monitoring period of unspecified duration between enumerated steps of the depicted embodiment. It will also be noted that each block of the block diagrams and/or flowchart diagrams, and combinations of blocks in the block diagrams and/or flowchart diagrams, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and code.

The description of elements in each figure may refer to elements of proceeding figures. Like numbers refer to like elements in all figures, including alternate embodiments of like elements.

Generally, the described embodiments initialize a plurality of expansion bus registers, each expansion bus register being associated with an expansion bus slot, monitor for flow control packets on an expansion bus; extract flow control data from the flow control packets, the flow control data relating to a plurality of expansion devices operating on the expansion bus, and write flow control data to the plurality of expansion bus registers based on the flow control packets. Some of the described embodiments include calculating an arrangement of the plurality of expansion devices that optimizes throughput based on the flow control data, wherein each of the plurality of expansion devices is coupled to one of the plurality of expansion bus slot.

As used herein, flow control is the management of data flow on an expansion bus, for example between a central processor and one or more expansion devices, so that the data can be handled at an efficient pace. Too much data arriving before a device can handle it causes data overflow, meaning the data is either lost or must be retransmitted. In a credit-based flow control scheme, a receiving device allocates to a transmitting device a number of flow control credits, wherein the transmitting device consumes flow control credits with each transmission and is only allow to transmit when there are available flow control credits. The initial number of flow control credits may be based on the buffer space or other receiving capability of the receiving device, wherein the receiving device allocates additional flow control credits to the transmitting device as the receiving device processes received data.

Flow control data is calculated and stored in expansion bus registers so as to be readily available. Flow control usage is not generally known or published. Further, similar devices from different manufacturers may have different flow control usage statistics. Based on the flow control data, an arrangement of expansion devices that optimized flow control usage may be calculated. Care is taken to ensure that the calculated arrangement improves throughput.

To calculate an arrangement of the plurality of expansion devices that optimizes throughput based on the flow control data, flow control limits are identified, flow control usage data is gathered from traffic using the expansion devices, and an optimization routine is performed to optimally assign expansion devices to expansion bus slots based on the flow control data.

FIG. **1** is a schematic block diagram illustrating one embodiment of a computer system **100** for optimizing expansion devices on a computer expansion bus based on real-time flow control data, according to embodiments of the disclosure. The system **100** includes, in one embodiment, a computing device **101**. The computing device **101** may include, but is not limited to, a server, a workstation, a mainframe computer, a supercomputer, a desktop computer, a laptop computer, a gaming console, a mobile phone, a smart phone, a tablet computer, or the like. The computing device **101** includes a flow control data module **102**, a processor **104**, a memory **106**, and an expansion bus **108**. The expansion bus **108** may itself include a plurality of expansion devices **110** *a-n* (collectively "**110**") coupled to a plurality of expansion bus slots **112** *a-n* (collectively "**110**"). Further, the expansion bus **108** may include a plurality of expansion bus registers **114***a-n* (collectively "**114**"). While depicted as residing in the expansion bus space, in other embodiments, the plurality of expansion bus registers **114** may reside in a basic input/output system ("BIOS") space, or in the memory **106**.

The flow control data module **102**, in one embodiment, is configured to initialize a plurality of expansion bus registers **114**, where each expansion bus register **114** is associated with one of a plurality of expansion bus slots **112**. The flow control data module **102** may also be configured to monitor for flow control packets on an expansion bus **108** and to extract flow control data from the flow control packets. The flow control data relates to a plurality of expansion devices **110** operating on the expansion bus **108**. The flow control data module **102** may further write flow control data to the plurality of expansion bus registers based on the flow control packets. In some embodiments, the flow control data module **102** may calculate an arrangement of the plurality of expansion devices **110** that optimizes throughput based on the flow control data.

The flow control data module **102** may include computer hardware, computer software, or a combination of both computer hardware and computer software. For example, the flow control data module **102** may include circuitry, or a processor, configured to monitor for flow control packets on an expansion bus. As another example, the flow control data module **102** may include computer program code that allows the processor **104** to extract flow control data from the flow control packets and/or write flow control data to the plurality of expansion bus registers. The flow control data module **102** is discussed in further detail with reference to FIGS. **2-3**, below.

The processor **104**, in one embodiment, may include any known controller capable of executing computer-readable

instructions and/or capable of performing logical operations. For example, the processor **104** may be a microcontroller, a microprocessor, a central processing unit ("CPU"), a graphics processing unit ("GPU"), an auxiliary processing unit, a field programmable gate array ("FPGA"), or similar programmable controller. In some embodiments, the processor **104** executes instructions stored in the memory **106** to perform the methods and routines described herein. The processor **104**, in one embodiment, is communicatively coupled to the flow control data module **102**, the memory **106**, and the expansion bus **108**.

The memory **106**, in one embodiment, is a computer readable storage medium. In some embodiments, the memory **106** includes volatile computer storage media. For example, the memory **106** may include a random access memory ("RAM"), including dynamic RAM ("DRAM"), synchronous dynamic RAM ("SDRAM"), and/or static RAM ("SRAM"). In some embodiments, the memory **106** includes non-volatile computer storage media. For example, the memory **106** may include a hard disk drive, a flash memory, or any other suitable non-volatile computer storage device. In some embodiments, the memory **106** includes both volatile and non-volatile computer storage media.

In some embodiments, the memory **106** stores data relating to optimizing expansion devices on a computer expansion bus based on real-time flow control data. For example, the memory **106** may store expansion bus parameters, expansion device arrangements, expansion device identifiers, flow control data, lists of candidate expansion devices or candidate expansion bus slots, and the like. In some embodiments, the memory **106** also stores program code and related data, such as an operating system or other controller algorithms operating on the computing device **101**.

The expansion bus **108** provides an interface between the processor **104** and one or more expansion devices **110**. The expansion bus **108** refers to the mechanical and electrical connections coupling the one or more expansion devices **110** to the processor **104**. In some embodiments, the expansion bus **108** complies with an industry standard, such as the Peripheral Component Interconnect ("PCI"), PCI extended ("PCI-X"), PCI Express ("PCIe"), and Accelerated Graphics Port ("AGP") standards.

As depicted, the plurality of expansion bus slots **112** may include slots **112***a*-**112***n* and the plurality of expansion bus registers **114** may include registers **114***a*-**114***n*. Each expansion bus slot **112** may receive an expansion device **110**, such as one of expansion devices **110***a*-**110***n*. While FIG. **1** depicts an equal number of expansion devices **110** and expansion bus slots **112**, in other embodiments the computing device **101** may include more expansion bus slots **112** than expansion devices **110** (e.g., the expansion bus **108** may include unused expansion bus slots **112**). Further, while FIG. **1** depicts an equal number of expansion bus slots **112** and expansion bus registers **114**, in other embodiments the computing device **101** may include more expansion bus registers **114** than expansion bus slots **112**.

The expansion devices **110** are auxiliary devices that add functionality to the computing system **101** via the expansion bus **108**. An expansion device may also be known as an expansion board, expansion card, adapter board, adapter card, or accessory card. Each expansion bus slot **112** is configured to communicatively couple the expansion device **110** to the processor **104**. In some embodiments, an expansion device **110** may be configured to provide additional processing capabilities to the computing device **101**. For example, the plurality of expansion devices **110** may include an additional CPU (e.g., a co-processor), a graphics card (e.g., having a GPU for graphics processing), a sound card (e.g., having a microprocessor for audio/voice signal processing), or other auxiliary processor.

In one embodiment, an expansion device **110** may be configured to provide additional data storage capabilities to the computing device **101**. For example, the plurality of expansion devices **110** may include a removable storage device adapter, an external storage device adapter, or the like. In some embodiments, the expansion device **110** may include a microprocessor (e.g., a storage controller) for controlling a storage device coupled to the expansion device **110**. In another embodiment, an expansion device **110** may be configured to provide networking capabilities to the computing device **101**. For example, the plurality of expansion devices **110** may include a wireless network adapter, a wired network adapter (e.g., an Ethernet adapter), a modem, or the like.

In certain embodiments, an expansion device **110** may be an adapter configured to couple an additional peripheral device to the computing device **101** and to convert data from one communication standard to another. For example, the expansion device **110** may be an adapter comprising a serial port (e.g., a serial ATA ("SATA")), a parallel port, a universal serial bus ("USB") port, or the like. In further embodiments, the expansion device **110** may be an adapter for adapting another expansion device that uses a different connecter and/or communication standard than provided by the expansion bus **108**. For instance, the expansion device **110** may be a PCIe adapter capable of receiving a personal computer memory card international association ("PCMCIA") standard card, an ExpressCard® device, or the like.

FIG. **2** is a schematic block diagram illustrating one embodiment of a flow control data apparatus **200** for optimizing expansion devices on a computer expansion bus based on real-time flow control data, according to embodiments of the disclosure. The flow control data apparatus **200** includes a flow control data module **102**, which may be substantially similar to the flow control data module **102** described above with reference to FIG. **1**. The flow control data module **102**, in one embodiment, includes a configuration module **202**, a packet module **204**, a flow control module **206**, and a register module **208**, which are described below. The modules **202**-**208** of the flow control data module **102** may be communicatively coupled to one another.

The configuration module **202**, in one embodiment, is configured to initialize a plurality of expansion bus registers **114**, each expansion bus register **114** being associated with one of the plurality of expansion bus slots **112**. The expansion bus registers **114** are located in the expansion bus **108**. In certain embodiments, each expansion bus slot **112** includes one or more expansion bus registers **114**. The configuration module **202** may initialize an expansion bus register **114** for each expansion bus slot **112** coupled to an expansion device **110**.

In some embodiments, the configuration module **202** initializes the expansion bus registers **114** by activating an otherwise unused expansion bus register **114**. For example, the configuration module **202** may activate an extended capability register, such as a Vendor Specific Extended Capability register found in a PCIe expansion bus. Initializing the expansion bus registers **114** may further include programming the expansion bus registers **114** and/or registering the expansion bus registers **114** to prevent other devices or processes from writing to the expansion bus registers **114**.

In certain embodiments, the configuration module **202** may identify available expansion bus registers **114** and allocate an expansion bus register **114** to each expansion bus slot **112** for storing flow control data. The flow control data relates to real-time flow control of an expansion device **110** coupled to that expansion bus slot **112**, as discussed below in further detail. For example, the configuration module **202** may identify an unused expansion bus register **114** for each expansion bus slot **112** coupled to an expansion device **110**. The configuration module **202** may assign the unused expansion bus registers **114** for storing flow control data. In another example, the configuration module **202** may reallocate a previously assigned expansion bus register **114** to an expansion bus slot **112** for storing flow control data relating to an expansion device **110** coupled to that expansion bus slot **112**.

In some embodiments, the configuration module **202** resets the plurality of expansion bus registers **114**. For example, the configuration module **202** may reset the expansion bus registers **114** in response to allocating the expansion bus registers **114** for storing flow control data. In another example, the configuration module **202** may reset the expansion bus registers **114** in response to a change in the arrangement of the plurality of expansion devices **110**, as discussed in further detail below.

The configuration module **202** beneficially allows tracking of flow control data. Conventionally, flow control data is not tracked by the expansion bus **108** and is only obtainable by attaching a protocol analyzer to the expansion bus **108**. The configuration module **202** allocates registers on the expansion bus **108** to store the flow control data, allowing the flow control data to be accessed within the computing device **101**. Conventionally, the expansion bus registers **114** are not used to store flow control data. The configuration module **202**, in one embodiment, repurposes some of the registers on the expansion bus, for example a set of extended capability registers, to store flow control data allowing for its access within the computing device **101**.

The packet module **204**, in one embodiment, is configured to monitor flow control packets on an expansion bus **108**. As used herein, monitoring flow control packets refers to receiving (e.g., intercepting) packets relating to flow control between an expansion bus slot **112** and its coupled expansion device **110**. In some embodiments, the flow control packets may indicate a number of flow control credits available to the expansion device **110**, the number of flow control credits relating to buffer space of the receiving device. In certain embodiments, the packet module **204** forwards flow control packets to the flow control module **206**, wherein the flow control module **206** extracts flow control data from the flow control packets. The packet module **204** may monitor for and report the flow control packets in real-time.

For example, a limited amount of flow control credits may be issued by a receiving device, wherein a transmitting device consumes the flow control credits with each transmission. The transmitting device may only transmit a packet if doing so will not cause the amount of consumed flow control credits to exceed its credit limit, so as not to overflow the receiving device's buffers. Flow control packets may be sent by the receiving device to update flow control credit limits at the transmitting device, thereby allowing the transmitting device to transmit additional packets without overflowing the receiving device's buffers.

In a further embodiment, different pools of flow control credits may be maintained for different types of data packets, wherein the flow control packets update a flow control credit limit for a particular pools of flow control credits. Examples of different flow control credit types include: posted requests transaction layer packet ("TLP") headers, posted requests TLP data, non-posted requests TLP headers, non-posted requests TLP data, completion TLP headers, completion TLP data, and the like. In some embodiments, the packet module **204** may monitor for any type of flow control packets, while in other embodiments the packet module **204** may monitor only for certain types of flow control packets.

The flow control module **206**, in one embodiment, is configured to calculate flow control data from the flow control packets, the flow control data relating to a plurality of expansion devices **110** operating on the expansion bus **108**. In certain embodiments, the flow control data may include: an average flow control usage for each expansion device, a ratio of average flow control usage to flow control limit for each expansion device, an average amount of unused flow control credits for each expansion device, and/or a number of times the expansion device reaches the flow control limit. In a further embodiment, the flow control data may include operating requirements and/or limitations of the expansion devices **110** and/or the expansion bus slots **112**, including lane width requirements, physical sizes, flow control limits, and the like. The flow control module **206**, in one embodiment, extracts flow control limits from the flow control packets to calculate the flow control data. For example, the flow control module **206** may calculate flow control usage and/or an amount of unused flow control credits based of the flow control packets.

In some embodiments, the flow control module **206** calculates the flow control data over a particular period of time. In one embodiment, the flow control module **206** may identify peak usage times of the computing device **101** and calculate the flow control data over the peak usage times. For example, the computing device **101** may be a web server whose peak usage time is a three-hour period from 11:00 AM to 2:00 PM. Thus, the flow control module **206** may calculate flow control data, such as flow control usage and/or an amount of unused flow control credits, over a 24-hour period or a shorter period centered on the peak usage time. In certain embodiments, an average flow control usage and/or an average amount of unused flow control credits is computed over the peak usage time. The peak usage time may be manually entered by a user and/or may be automatically determined by the flow control module **206**. In certain embodiments, the flow control module **206** may identify a number of times the expansion device **110** reaches the flow control limit during the peak usage time.

In some embodiments, the flow control module **206** identifies an initial flow control credit limit for each expansion bus slot **112**. For example, the packet module **204** may intercept a flow control packet announcing the initial limit, wherein the flow control module **206** identifies the initial flow control limit from the flow control packets. Specifically, an "InitFC" packet on a PCIe bus may be intercepted and parsed to identify the initial flow control credit limit for each expansion bus slot **112**. The initial flow control limit may then be used by the flow control module **206** to calculate a ratio of average flow control usage to flow control limit for each expansion device (e.g., a percentage of the initial flow control credit limit used, on average, by the expansion device). In response to calculating the flow control data, the flow control module **206** reports the flow control data to the register module **208**, wherein the register module **208** writes the flow control data to the expansion bus registers **114**. In certain embodiments, the flow control module **206** may continuously calculate the flow control

data based on the received flow control packets, for example by updating the flow control data as each flow control packet is received. In some embodiments, the flow control module **206** may report the flow control data to the register module **208** at regular intervals, such as every second, minute, hour, or the like.

The register module **208**, in one embodiment, is configured to write flow control data to the plurality of expansion bus registers **114**. In some embodiments, the register module **208** may be a controller or driver for writing data to the expansion bus registers **114**. The register module **208** receives the flow control data from the flow control module **206**. For example, the register module **208** may periodically receive reports from the flow control module **206** which include the flow control data, wherein the register module **208** writes the flow control data to the plurality of expansion bus registers **114** in response to receiving a report. As an example, a report from the flow control module **206** may include updated values for an average flow control usage for each expansion device, a ratio of average flow control usage to flow control limit for each expansion device, an average amount of unused flow control credits for each expansion device, and/or a number of times the expansion device reaches the flow control limit. In certain embodiments, the register module **208** overwrites previous flow control data in the expansion bus registers **114** with the updated values.

FIG. **3** is a schematic block diagram illustrating another embodiment of a flow control data apparatus **300** for optimizing expansion devices on a computer expansion bus based on real-time flow control data, according to embodiments of the disclosure. The flow control data apparatus **300** includes a flow control data module **102**, which may function substantially similar to the flow control data module **102** described above with reference to FIG. **1**. The flow control data module **102**, in one embodiment, includes a configuration module **202**, a packet module **204**, a flow control module **206**, and a register module **208**, which may be substantially similar to those described in relation to the apparatus **200** of FIG. **2**. In some embodiments, the flow control data module **102** may also include: an optimization module **302**, a relocation module **304**, an allocation module **306**, a reset module **308**, a slot limit module **310**, a candidate module **312**, a placement module **314**, a priority module **316**, and/or a capability module **318**, which are described below. The modules **202-208** and **302-318** of the flow control data module **102** may be communicatively coupled to one another.

The configuration module **202** may be substantially described above with reference to FIG. **2**. In some embodiments, the configuration module **202** further includes an allocation module **306** and/or a reset module **308**. The allocation module **306**, in one embodiment, is configured to identify an unused expansion bus register **114** for each expansion bus slot **112**. In some embodiments, the allocated expansion bus register **114** may be an extended capability register, for example a Vendor-Specific Extended Capability ("VSEC") register found in a PCIe expansion bus. The allocation module **306**, in certain embodiments, may identify one or more candidate expansion bus registers **114** for each expansion bus slot **112** and determine whether the candidate expansion bus registers **114** are available for use in storing flow control data (e.g., whether they are unused). For example, the allocation module **306** may check a registry to determine whether the candidate expansion bus registers **114** are available.

The allocation module **306** is further configured to allocate the identified expansion bus registers **114** for storing flow control data for each expansion bus slot **112**. In certain embodiments, the allocation module **306** may register the expansion bus registers **114** with a registry to prevent another device, module, and/or application from using the allocated expansion bus registers **114**, so as to prevent corruption of the flow control data. In some embodiments, the allocation module **306** may allocate storage space outside the expansion bus **108** for storing the flow control data. For example, the allocation module **306** may reserve storage space in non-volatile storage media of the computing device **101** in order to preserve older flow control data for future comparison and/or in response to being unable to locate unused expansion bus registers **114**.

In some embodiments, the allocation module **306** indicates the allocated expansion bus registers **114** to the reset module **308**, wherein the reset module **308** erases data values already stored in the allocated expansion bus registers **114**. In other embodiments, the register module **208** may simply overwrite data values already stored in the expansion bus registers **114**, in response to the allocation module **306** identifying and assigning expansion bus registers **114** for storing flow control data.

The reset module **308**, in one embodiment, is configured to delete data values stored in the plurality of expansion bus registers **114** allocated for storing flow control data in response to the allocation module **306** assigning an expansion bus register **114** to each expansion bus slot **112**. In some embodiments, the reset module **308** may be further configured to delete data values stored in the expansion bus registers **114** in response to at least one expansion device **110** being relocated, wherein the register module **208** writes new flow control data to the plurality of expansion bus registers **114** based on the relocated expansion device **110**.

The optimization module **302**, in one embodiment, is configured to calculate an arrangement (e.g., a placement order) of the plurality of expansion devices **110**, based on the flow control data, to maximize expansion bus **108** throughput. In some embodiments, data transfer from certain expansion devices **110** may be limited by flow control constraints, such as a flow control limit of the expansion bus slot **112** to which the expansion device **110** is coupled. The optimization module **302** reads flow control data (e.g., flow control metrics and/or statistics) relating to the expansion devices **110** and calculates an arrangement of the expansion devices (e.g., a mapping of which expansion device **110** is to be placed in which expansion bus slot **112**) based on the flow control data.

In some embodiments, the optimization module **302** considers the average flow control usage of the expansion devices **110** when calculating an optimal arrangement of the expansion devices based on flow control data. In certain embodiments, the optimization module **302** may consider additional flow control data, such as a ratio of average flow control usage to flow control limit for each expansion device, an average amount of unused flow control credits for each expansion device, and/or a number of times the expansion device reaches the flow control limit. In some embodiments, the optimization module **302** includes a slot limit module **310**, a candidate module **312**, a placement module **314**, a priority module **316**, and/or a capability module **318** which assist in calculating an optimal arrangement of the expansion devices based on flow control data, as described below.

The optimization module **302** begins with assigning the expansion device **110** having the highest average flow control usage and that is sufficiently near the flow control limit of its expansion bus slot **112** (e.g., within a threshold

percentage of the flow control limit) and continues to assigns those expansion devices **110** sufficiently near the flow control limit of their expansion bus slots **112**, in order from highest to lowest average flow control usage, until all expansion devices **110** are assigned to expansion bus slots **112**. If an expansion device **110** is not sufficiently near the flow control limit of its expansion bus slot **112**, then the optimization module **302** may tentatively assign it to its current expansion bus slot **112** unless another expansion device **110** of higher average flow control usage is assigned to that expansion bus slot **112**, as described below in greater detail.

Upon assigning all expansion devices **110** to an expansion bus slot **112**, the optimization module **302** may instruct a user to rearrange the expansion devices **110** into the assigned locations. In some embodiments, the optimization module **302** may instruct the user to rearrange the expansion devices **110** between assigning expansion devices **110** to expansion bus slots **112**. For example, the optimization module **302** may assign the expansion device **110** having the highest average flow control usage, instruct the user to swap the expansion device **110** into its new expansion bus slot **112**, and calculate a location for the expansion device **110** having the next highest average flow control usage after the swap. In certain embodiments, the optimization module **302** may determine a placement order of the expansion devices **110**, instruct the user to move the expansion devices **110**, and recalculate the placement order in response to the expansion devices **110** being moved. The optimization module may continue to recalculate the placement order until the calculated placement order matches a current placement order, thereby indicating that the current placement order is an optimal arrangement of the expansion devices **110**.

The slot limit module **310**, in one embodiment, is configured to identify flow control limits for each of the plurality of expansion bus slots **112**. For example, the slot limit module **310** may monitor configuration data for each expansion bus slot **112** on the expansion bus **108**. In some embodiments, the slot limit module **310** monitors for packets sent on the expansion bus announcing an initial flow control limits (e.g., for a link comprising an expansion device and an expansion slot coupling the expansion device to the expansion bus). The initial flow control limits may be stored, for example in the expansion bus registers **114**, wherein the slot limit module **310** reads the flow control limits from the expansion bus registers.

The candidate module **312**, in one embodiment, is configured to determine at least one candidate device from the plurality of expansion devices **110**. The candidate module **312** compares, for each of the plurality of expansion bus slots **112**, an average flow control usage for an expansion device **110** using the expansion bus slot **112** to an identified operating limit for the expansion bus slot **112**, wherein the candidate module **312** determines at least one candidate device based on the comparison. In certain embodiments, the flow control data includes average flow control usage for each of the plurality of expansion devices **110**.

To be a candidate device, an expansion device **110** may have an average flow control usage that is within a predetermined amount of the expansion bus slot currently coupled to the expansion device. In some embodiments, the predetermined amount is a threshold percentage of the flow control limit (e.g., 90%, 95%, or even 100% of the flow control limit). Alternatively, to be a candidate device, an expansion device may have an average amount of unused flow control credits less than a threshold amount. Each candidate device is associated with an incumbent slot. As used herein, an incumbent slot refers to an expansion bus slot **112** currently coupled with the candidate device.

In some embodiments, the candidate module **312** determines whether any candidate devices exist. In response to no candidate devices existing, the candidate module **312** may signal the optimization module **302** that the current arrangement of expansion devices **110** is an optimal arrangement of the expansion devices **110**. Otherwise, the candidate module **312** may generate a list of candidate devices and provide the list to the placement module **314**. In certain embodiments, the candidate module **312** provides the list of candidate devices by accessing a mapping structure storing a current arrangement of the expansion devices and expansion bus slots so as to indicate, within the mapping structure, those expansion devices which qualify as candidate devices. For example, an entry in the mapping structure corresponding to a candidate device may be flagged to indicate that the expansion device is a candidate device.

In some embodiments, the candidate module **312** is further configured to determine at least one candidate slot for a candidate device, from among the plurality of expansion bus slots **112**. For example, the candidate module **312** may compare, for each of the plurality of expansion bus slots **112**, a flow control limit to the average flow control usage of the candidate device. To be a candidate slot, an expansion bus slot **112** must have a flow control limit larger than the average flow control usage of the selected candidate device and it must be physically compatible with the candidate expansion device. In certain embodiments, the candidate module **312** queries the capability module **318**, wherein the capability module **318** determines whether an expansion bus slot **112** is physically compatible with the candidate expansion device, as discussed below in further detail. In some embodiments, the candidate slot may be associated with an incumbent device. As used herein, an incumbent device refers to an expansion device currently coupled with the candidate slot. In other embodiments, the candidate slot may be empty.

The placement module **314**, in one embodiment, is configured to assign each candidate expansion device **110** to one of the plurality of expansion bus slots **112** based on the average flow control usage and the flow control limits. In some embodiments, the placement module **314** first assigns the candidate device with the highest average flow control usage and proceeds to assign the remaining candidate devices from highest to lowest average flow control usage. In certain embodiments, the placement module **314** may query the priority module **316** for a ranking of candidate devices from highest to lowest average flow control usage, wherein the placement module **314** assigns each candidate expansion device to one of the plurality of expansion bus slots **112** in an order based on the ranking of each candidate expansion device.

The placement module **314**, in one embodiment, identifies a candidate expansion device having the highest average flow control usage and identifies a candidate expansion bus slot having a highest flow control limit. In certain embodiments, the placement module **314** queries the candidate module **312** for a list of at least one candidate expansion bus slot for the identified candidate device from among the plurality of expansion bus slots **112**. As discussed above, each candidate expansion bus slot must have a flow control limit larger than the average flow control usage of the candidate expansion device and be physically compatible with the candidate expansion device. In some embodiments, the candidate module **312** determines whether an expansion device **110** is a candidate for rearrangement (e.g., a candi-

date device). The candidate module **312** further identifies one or more candidate expansion bus slots among the plurality of expansion bus slots **112** for each candidate device. For example, the candidate module **312** may determine whether an expansion bus slot **112** has a flow control limit larger than the average flow control usage of the candidate expansion device while the capability module **318** determines whether the expansion bus slot **112** is physically compatible with the candidate expansion device.

In some embodiments, the placement module **314** identifies an incumbent expansion device located in the candidate expansion bus slot and verifies that the incumbent expansion device is physically compatible with the incumbent expansion bus slot. In certain embodiments, the placement module **314** queries the capability module **318** to determine whether the incumbent expansion device is physically compatible with the incumbent expansion bus slot. In response to an incumbent expansion device not being physically compatible with the incumbent expansion bus slot, the placement module **314** removes the candidate slot hosting the physically incompatible incumbent expansion device from the list of candidate slots.

In one embodiment, the placement module **314** verifies the average flow control usage of the incumbent expansion device is less than or equal to the average flow control usage of the candidate expansion device. In response to the average flow control usage of the incumbent expansion device being greater than the average flow control usage of the candidate expansion device, the placement module **314** removes the candidate slot from the list of candidate slots, as moving the candidate device to the candidate slot will worsen performance of the expansion bus **108**. In some embodiments, the placement module **314** accesses the flow control data stored in the expansion bus registers **114** and compares the average flow control usage of the incumbent expansion device to the average flow control usage of the candidate expansion device.

The placement module **314** assigns the selected candidate device to the candidate slot with the highest flow control limit that also meet the above criteria (e.g., incumbent device physically compatible, not of greater average flow control usage, etc.). If the list of candidate slots becomes empty, then the placement module **314** assigns the candidate device to its current expansion bus slot **112**. After assigning the candidate device with the highest average flow control usage to an expansion bus slot **112**, the placement module **314** proceeds to iteratively assign any remaining candidate devices in the same manner, in order from highest to lowest average flow control usage, until all candidate devices have been assigned to expansion bus slots **112**. In some embodiments, once an expansion bus slot **112** is assigned to a candidate device, that same expansion bus slot **112** is not considered by the placement module **314** when subsequently placing any remaining candidate devices, so as to consider a lesser number of candidate slots, thereby improving speed of placement.

The priority module **316**, in one embodiment, is configured to rank the at least one candidate expansion device **110** based on highest average flow control usage. In some embodiments, the priority module **316** receives a list of candidate devices from among the plurality of expansion devices **110** and acquires average flow control usage for each candidate device. In some embodiments, the flow control data stored in the expansion bus registers **114** includes average flow control usage for each expansion device **110**. In other embodiments, the average flow control usage may be computed from the flow control data stored in the expansion bus registers **114**. In response to receiving the average flow control usage for each candidate device, the priority module **316** ranks the candidate devices, for example from highest average flow control usage to lowest average flow control usage. In some embodiments, the priority module **316** indicates a candidate device's ranking in the list of candidate devices.

The compatibility module **318**, in one embodiment, is configured to compare a physical size of an expansion device **110** to a size supported by an expansion bus slot **112**, wherein the placement module **314** assigns each candidate expansion device **110** to one of the plurality of expansion bus slots **112** based on the size comparison. Each of the plurality of expansion devices **110** may have a connection of different sizes based on the purpose the particular expansion device **110**. For example, an expansion device **110** that is a graphics card may have a physically larger connection to support greater bandwidth of data transfer, while an expansion device **110** that is a networking card may have a physically smaller connection to support a lesser bandwidth. Similarly, each of the plurality of expansion bus slots **112** may have a connection of different size.

In some embodiments, the compatibility module **318** identifies configuration data for each of the plurality of expansion bus slots **112**, the configuration data indicating a physical size and/or a lane width size of the expansion bus slot **112**. For example, in a PCIe system a first PCIe slot (e.g., expansion bus slot **112***a*) may be physically sized to support up to 16 lanes, while a second PCIe slot (e.g., expansion bus slot **112***n*) may be physically sized to support up to 4 lanes, wherein each lane is a physical electrical connection for transferring data on the PCIe bus. In this example, a PCIe adapter with four lanes is be coupled to either PCIe slot, while a PCIe adapter with eight lanes may only couple to the first PCIe slot (e.g., the **16** lane PCIe slot). The compatibility module **318** further identifies a physical size of expansion device **110** coupled to a particular expansion bus slot **112**. In certain embodiments, the compatibility module **318** receives configuration information from an expansion device **110** indicating a physical size of expansion device **110**.

In response to identifying physical sizes of the plurality of expansion bus slots **112** in the plurality of expansion devices **110**, the compatibility module **318** determines whether a particular expansion device **110** will physically fit in a particular expansion bus slot **112**. For example, the compatibility module **318** may determine into which of the plurality of expansion bus slots **112** a candidate device will physically fit. As another example, the compatibility module **318** may determine whether an incumbent device already located in a candidate slot will physically fit in an incumbent slot already occupied by the candidate device. In response to comparing a physical size of expansion device **110** to a physical size of an expansion bus slot **112**, the compatibility module **318** may return, to the placement module **314** and/or the optimization module **302**, an indication of whether the expansion device **110** will physically fit into the expansion bus slot **112**.

In some embodiments, the compatibility module **318** is further configured to compare an electrical connection requirement of an expansion device **110** to a number of electrical connections provided by an expansion bus slot **112**, wherein the placement module **314** assigns an expansion device **110** to one of the plurality of expansion bus slots **112** based on the number of electrical connections. Each expansion bus slot **112** may comprise a maximum number of electrical connections, wherein the expansion bus slot **112**

may provide up to the maximum number of electrical connections to an expansion device **110**. Additionally, an expansion device **110** may require a minimum number of electrical connections for proper function. The compatibility module **318** identifies the minimum number of electrical connections required by the expansion device **110** as well as the maximum number of electrical connections provided by the expansion bus slot **112**. The compatibility module **318** then compares these numbers to determine whether the expansion bus slot **112** provides at least the minimum number of electrical connections required by the expansion device **110**.

The relocation module **304**, in one embodiment, is configured to prompt a user to relocate at least one of the plurality of expansion devices **110** into a different expansion bus slot **112**. In some embodiments, the capability module **318** may prompt the user via visual indicator, audible indicator, or combinations thereof. In certain embodiments, the prompt may be a message indicating that an arrangement optimizing the expansion devices **110** based on flow control has been calculated, wherein the message further indicates the calculated arrangement. In certain embodiments, the prompt may include instructions for swapping expansion devices **110**, including specific locations for the expansion devices **110**, a specific order in which the expansion devices **110** should be placed, and the like.

In some embodiments, the relocation module **304** sends the prompt to a second computing device, such as an electronic device used by an administrator tasked with swapping the expansion devices **110**. The second computing device may include, but is not limited to, a mobile phone, a smart phone, a tablet computer, a laptop computer, a desktop computer, a portable gaming console, or the like. The second computing device displays the prompt, which may include the calculated arrangement optimizing the expansion devices **110** based on flow control and/or instructions for swapping expansion devices **110**. Thus, the administrator may refer to the arrangement and/or instructions using the second computing device, while relocating the expansion devices **110** of the computing device **101**.

In certain embodiments, the relocation module **304** determines whether the expansion device **110** have been relocated. In one embodiment, the relocation module **304** compares expansion device identifiers (e.g., current values to previous values) to determine whether the expansion device **110** have been relocated. For example, the relocation module **304** may store a table mapping expansion device identifiers to expansion bus slot identifiers at the time the arrangement is calculated and periodically compare current expansion device identifiers to the table. In a further embodiment, the relocation module **304** may compare current expansion device identifiers to expected identifiers based on the calculated arrangement of expansion devices **110**, so as to determine whether the expansion devices **110** have been arranged into the calculated arrangement.

In some embodiments, one or more of the expansion devices **110** may be hot-swappable, meaning one expansion device **110** may be removed from its expansion bus slot **112** while the computing device **101** remains powered on (e.g., in operation) and another expansion device **110** placed in the vacated expansion bus slot **112** while the computing device **101** remains powered on. Accordingly, the relocation module **304** may store an identifier of the expansion devices **110** coupled to the expansion bus slots **112** at the time the arrangement is calculated, determine whether an expansion device **110** is removed during operation of the computing device **101**, determine that an expansion device **110** is placed into the recently vacated expansion bus slot **112**, read an identifier of the newly placed expansion device **110**, and compare the identifiers to determine whether an different expansion device **110** has been swapped into the expansion bus slot **112**.

In some embodiments, one or more of the expansion devices **110** may not be hot-swappable, meaning one expansion device **110** may only be removed from its expansion bus slot **112** after the computing device **101** is powered down (e.g., in operation) and another expansion device **110** placed in the vacated expansion bus slot **112** while the computing device **101** remains powered down. Accordingly, the relocation module **304** may store an identifier of the expansion devices **110** coupled to the expansion bus slots **112** at the time the arrangement is calculated, read the identifiers of the expansion devices **110** located in the expansion bus slots **112** when the computing device **101** is powered on, and compare the identifiers to determine whether any of the expansion devices **110** have been swapped.

In some embodiments, the relocation module **304** may again prompt the user to relocate the expansion devices **110** in response to determining that the expansion devices **110** have not been relocated (or, alternatively, that the expansion devices **110** have not been arranged into the calculated arrangement). In further embodiments, the relocation module **304** may refrain from again prompting the user to relocate the expansion devices **110** if a predetermined time period has not passed, so as to not annoy the user. For example, the relocation module **304** may again prompt the user if no relocation of the expansion devices **110** is detected in a predetermined time period, such as an hour or day (or fractions thereof). In response to determining that the expansion devices **110** have been relocated, the relocation module **304** may signal the reset module **308** of the new arrangement, wherein the reset module **308** erases the expansion bus registers **114** and the flow control module **206** calculates new flow control data based on the relocated expansion devices **110**.

FIG. **4** is a schematic flow chart diagram illustrating one embodiment of a method **400** for optimizing expansion devices on a computer expansion bus based on real-time flow control data, according to embodiments of the disclosure. In some embodiments, the method **400** is performed by a computing device, such as the computing device **101** described above with reference to FIG. **1**. In other embodiments, the method **400** may be performed by an apparatus for optimizing expansion devices on a computer expansion bus based on real-time flow control data, such as the flow control data apparatus **200** and/or the flow control data apparatus **300** described above with reference to FIGS. **2-3**. In certain embodiments, the method **400** may be performed by a processor executing program code, for example, a microcontroller, a microprocessor, a central processing unit ("CPU"), a graphics processing unit ("GPU"), an auxiliary processing unit, a FPGA, or the like.

The method **400** begins and initializes **402** a plurality of expansion bus registers, for example, the expansion bus registers **114**. In one embodiment, the configuration module **202** initializes **402** the plurality of expansion bus registers. Each expansion bus register is associated with one of a plurality of expansion bus slots, for example, the expansion bus slots **112**. In one embodiment, initializing **402** the plurality of expansion bus registers includes allocating an extended capability register, such as a Vendor-Specific Extended Capability (VSEC) register found in a PCIe expansion bus, for each expansion bus slot for storing flow control data. In another embodiment, initializing **402** the

plurality of expansion bus registers includes identifying an unused expansion bus register for each expansion bus slot, allocating the identified registers for storing flow control data, and resetting data values stored in the allocated expansion bus registers.

The method **400** monitors **404** for flow control packets on an expansion bus and extracts **406** flow control data from the flow control packets. In one embodiment, the packet module **204** monitors **404** for flow control packets on an expansion bus and the flow control module **206** extracts **406** flow control data from the flow control packets. The flow control data, in one embodiment, relates to a plurality of expansion devices operating on the expansion bus, for example, the expansion devices **110** operating on the expansion bus **108**. In certain embodiments, monitoring **404** for flow packets includes listening for data link layer flow packets exchanged between an expansion slot and an expansion device coupled to the expansion slot. In some embodiments, extracting **406** flow control data from the flow control packets includes calculating a number of available flow control credits.

The method **400** writes **408** flow control data to the plurality of expansion bus registers based on the flow control packets. The method **400** ends. In one embodiment, the register module **208** writes **408** the flow control data to the plurality of expansion bus registers. In certain embodiments, writing **408** flow control data includes storing average flow control usage for each of the plurality on expansion devices. The average flow control usage for an expansion device is written **408** to the expansion bus register associated with the expansion bus slot coupled to the expansion device. Additionally, writing **408** flow control data may include storing flow control limits for each of the plurality of expansion bus slots.

FIG. **5** is a schematic flow chart diagram illustrating a method **500** for optimizing expansion devices on a computer expansion bus based on real-time flow control data, according to embodiments of the disclosure. In some embodiments, the method **500** is performed by a computing device, such as the computing device **101** described above with reference to FIG. **1**. In other embodiments, the method **500** may be performed by an apparatus for optimizing expansion devices on a computer expansion bus based on real-time flow control data, such as the flow control data apparatus **200** and/or the flow control data apparatus **300** described above with reference to FIGS. **2-3**. In certain embodiments, the method **500** may be performed by a processor executing program code, for example, a microcontroller, a microprocessor, a central processing unit ("CPU"), a graphics processing unit ("GPU"), an auxiliary processing unit, a FPGA, or the like.

The method **500** begins and initializes **502** a plurality of expansion bus registers, for example, the expansion bus registers **114**. In one embodiment, the configuration module **202** initializes **502** the plurality of expansion bus registers. Each expansion bus register is associated with one of a plurality of expansion bus slots, for example, the expansion bus slots **112**. In one embodiment, initializing **502** the plurality of expansion bus registers includes allocating an extended capability register (for example, a Vendor Specific Extended Capability ("VSEC") register) for each expansion bus slot for storing flow control data and resetting data values stored in the allocated registers.

The method **500** monitors **504** for flow control packets on an expansion bus and calculates **506** flow control data from the flow control packets. In one embodiment, the packet module **204** monitors **504** for flow control packets on an expansion bus and the flow control module **206** calculates **506** flow control data from the flow control packets. In response to calculating **506** flow control data, the method **500** writes **508** the flow control data to the plurality of expansion bus registers. In one embodiment, the register module **208** writes **508** the flow control data to the plurality of expansion bus registers. In certain embodiments, writing **508** flow control data includes storing average flow control usage for each of the plurality on expansion devices, a ratio of average flow control usage to flow control limit for each expansion device, an average amount of unused flow control credits, and/or storing flow control limits for each of the plurality of expansion bus slots.

The method **500** calculates **510** an arrangement that optimizes throughput of the plurality of expansion devices based on the flow control data. In one embodiment, the optimization module **302** calculates **510** an arrangement that optimizes throughput of the plurality of expansion devices based on the flow control data. Each of the plurality of expansion devices is coupled to one of the plurality of expansion slot. In some embodiments, the number of expansion slots is greater than the number of expansion devices. In other embodiments, the number of expansion slots is equal to the number of expansion devices.

Calculating **510** the arrangement of expansion devices optimizing throughput of the expansion devices may include assigning expansion devices to specific expansion bus slots, based on the flow control data, to maximize expansion bus throughput. In some embodiments, data transfer from certain expansion devices may be limited by flow control constraints, such as a flow control limit of the expansion bus slot to which the expansion device is coupled. Calculating **510** the arrangement optimizing throughput of the expansion devices may include identifying a flow control constrained expansion device and assigning it to an expansion bus slot with a higher flow control limit. In certain embodiments, calculating **510** the arrangement of expansion devices may include prioritizing expansion devices, wherein flow control constrained expansion device with higher average flow control usage are assigned to expansion bus slots with higher flow control limits. Calculating **510** the arrangement of expansion devices is discussed in further detail below, with reference to FIG. **6**.

The method **500** prompts **512** a user to relocate at least one of the plurality of expansion devices into a different expansion bus slot based on the calculated arrangement. In one embodiment, the relocation module **304** prompts **512** a user to relocate at least one of the plurality of expansion devices into a different expansion bus slot based on the calculated arrangement. In some embodiments, prompting **512** the user to relocate an expansion device includes presenting a visual indicator, audible indicator, or combinations thereof. In certain embodiments, prompting **512** the user to relocate an expansion device includes indicating that an arrangement optimizing the expansion devices based on flow control has been calculated and further indicating the calculated arrangement. In another embodiment, prompting **512** the user to relocate an expansion device includes giving instructions for swapping expansion devices, including specific locations for the expansion devices, a specific order in which the expansion devices should be placed, and the like.

In some embodiments, prompting **512** the user to relocate an expansion device includes sending a message to a second computing device, such as an electronic device used by an administrator tasked with swapping the expansion devices. Prompting **512** the user to relocate an expansion device may further include second computing device displaying the message, which may include the calculated arrangement

optimizing the expansion devices based on flow control and/or instructions for swapping expansion devices.

The method **500** determines **514** whether the expansion devices have been relocated. In one embodiment, the relocation module **514** determines **514** whether the expansion devices have been relocated. In some embodiments, determining **514** whether the expansion devices been relocated includes storing an identification number for each expansion device coupled to an expansion bus slot (for example, when calculating **510** the arrangement optimizing throughput of the expansion devices), reading, for each expansion bus slot, an identification number of a currently attached expansion device, and comparing the stored identification numbers to the read identification numbers.

In response to determining **514** that the expansion devices have been relocated, the method **500** proceeds to write **516** new flow control data to the plurality of expansion bus registers based on the relocated expansion device. In one embodiment, the register module **208** writes **516** new flow control data to the plurality of expansion bus registers based on the relocated expansion device. Otherwise, in response to determining **514** that the expansion devices have not been relocated, the method **500** may proceed to again prompt **512** the user to relocate the expansion devices. In one embodiment, the relocation module **304** again prompts **512** the user to relocate the expansion devices. Alternatively, the method **500** may continue to monitor for relocation of expansion devices without again prompting **512** the user to relocate expansion devices. The method **500** ends. In one embodiment, the relocation module **304** continues to monitor for relocation of expansion devices without again prompting **512** the user to relocate expansion devices.

In some embodiments, writing **516** the new flow control data includes resetting the plurality of expansion bus registers. In further embodiments, writing **516** the new flow control data includes storing the old flow control data to nonvolatile storage medium (such as flash memory, hard disk drive, or the like) and overwriting data stored in the expansion bus registers with the new data. The old flow control data (stored in nonvolatile storage) may be used at a later point in time to evaluate the calculated arrangement.

FIG. **6** is a schematic flow chart diagram illustrating a method **600** for calculating an arrangement of the plurality of expansion devices that optimizes throughput based on the flow control data, according to embodiments of the disclosure. In some embodiments, the method **600** is performed by a computing device, such as the computing device **101** described above with reference to FIG. **1**. In other embodiments, the method **600** may be performed by an apparatus for optimizing expansion devices on a computer expansion bus based on real-time flow control data, such as the flow control data apparatus **200** and/or the flow control data apparatus **300** described above with reference to FIGS. **2-3**. In certain embodiments, the method **600** may be performed by a processor executing program code, for example, a microcontroller, a microprocessor, a central processing unit ("CPU"), a graphics processing unit ("GPU"), an auxiliary processing unit, a FPGA, or the like.

The method **600** begins and reads **602** flow control data stored in a plurality of expansion bus registers, such as the expansion bus registers **114**. In one embodiment, the slot limit module **310** reads **602** the flow control data stored in a plurality of expansion bus registers. In certain embodiments, the flow control data includes an average flow control usage for each expansion device, a ratio of average flow control usage to flow control limit for each expansion device, and/or an average amount of unused flow control credits for each expansion device. Flow control data may be stored in the expansion bus registers **114** during operation of the computer system, as discussed above.

The method **600** also identifies **604** flow control limits for each expansion bus slot. In one embodiment, the slot limit module **310** identifies **604** flow control limits for each expansion bus slot. In some embodiments, identifying **604** flow control limits includes monitoring for packets sent on the expansion bus announcing an initial flow control limits (e.g., for a link comprising an expansion device and an expansion slot coupling the expansion device to the expansion bus). The initial flow control limits may be stored, for example in the expansion bus registers **114**, wherein identifying **604** flow control limits includes reading the flow control limits from the expansion bus registers.

The method **600** determines **606** whether any candidate devices exist based on the flow control data and the flow control limits. In one embodiment, the candidate module **312** determines **606** whether any candidate devices exist based on the flow control data and the flow control limits. For example, determining **606** whether any candidate devices exist may include comparing, for each of the plurality of expansion devices, an average flow control usage to a flow control limit of the expansion bus slot coupled to the expansion device. To be a candidate device, an expansion device may have an average flow control usage that is within a predetermined amount of the expansion bus slot currently coupled to the expansion device. In some embodiments, the predetermined amount is a threshold percentage of the flow control limit (e.g., 90%, 95%, or even 100% of the flow control limit). Alternatively, to be a candidate device, an expansion device may have an average amount of unused flow control credits less than a threshold amount.

In some embodiments, determining **606** whether any candidate devices exist may include accessing a mapping structure storing a current arrangement of the expansion devices and expansion bus slots so as to indicate, within the mapping structure, those expansion devices which qualify as candidate devices. For example, an entry in the mapping structure corresponding to a candidate device may be flagged to indicate that the expansion device is a candidate device.

In response to determining **606** that one or more candidate devices exists, the method **600** selects **608** a candidate device having the highest average flow control usage from among one or more candidate devices. In one embodiment, the candidate module **312** selects **608** a candidate device having the highest average flow control usage from among one or more candidate devices. Otherwise, in response to determining **606** that no candidate devices exist, the method **600** ends. Selecting **608** the candidate device having the highest average flow control usage may include selecting a first candidate device on a list of candidate devices. For example, the priority module **316** may sort a list of the one or more candidate devices according to average flow control usage, wherein the optimization module **302** and/or the candidate module **312** selects the first candidate device on the list.

The method **600** next determines **610** whether any candidate slots exist for the selected candidate device from among the plurality of expansion bus slots. In one embodiment, the candidate module **312** determines **610** whether any candidate slots exist for the selected candidate device from among the plurality of expansion bus slots. In certain embodiments, determining **610** whether any candidate slots exist may include comparing, for each of the plurality of expansion bus slots, a flow control limit to the average flow

control usage of the candidate device. Additionally, determining **610** whether any candidate slots exist may include determining whether an expansion bus slot is physically compatible with the selected candidate device. To be a candidate slot, an expansion bus slot must be physically compatible with the candidate expansion device and have a flow control limit larger than the average flow control usage of the selected candidate device.

In response to determining **610** that one or more candidate slots exists for the selected candidate device, the method **600** selects **612** a candidate slot having a highest flow control limit from among the one or more candidate slots. In one embodiment, the placement module **314** selects **612** a candidate slot having a highest flow control limit from among the one or more candidate slots. Otherwise, in response to determining **610** that no candidate slots exist, the method **600** determines **626** whether there are any additional candidate devices among the one or more candidate devices. In one embodiment, the placement module **314** determines **626** whether there are any additional candidate devices among the one or more candidate devices. Selecting **612** the candidate slot with a highest flow control limit, in one embodiment, may include accessing flow control limits for the candidate devices.

The selected candidate device is associated with an incumbent slot. As used herein, an incumbent slot refers to an expansion bus slot currently coupled with the candidate device. In some embodiments, the selected candidate slot may be associated with an incumbent device. As used herein, an incumbent device refers to an expansion device currently coupled with the candidate slot. In other embodiments, the selected candidate slot may be empty.

The method **600** next determines **614** whether both the candidate slot and the incumbent slot are physically capable of coupling to both the candidate device and the incumbent device. In one embodiment, the capability module **318** determines **614** whether both the candidate slot and the incumbent slot are physically capable of coupling to both the candidate device and the incumbent device. Determining **614** whether both slots fit both devices ensures that the method **600** does not generate a physically impossible arrangement.

In response to determining **614** that both slots fit both devices, the method **600** proceeds to determine **616** whether the average flow control usage of the candidate device is greater in value than the average flow control usage of the incumbent device. In one embodiment, the placement module **314** determines **616** whether the average flow control usage of the candidate device is greater in value than the average flow control usage of the incumbent device. In response to the candidate slot being empty, the method **600** also determines **616** whether the average flow control usage of the candidate device is greater in value than the average flow control usage of the incumbent device. Otherwise, in response to determining **614** that both slots do not fit both devices, the method **600** proceeds to determine **622** whether there are any additional candidate slots among the one or more candidate slots (e.g., whether there are any candidate slots not yet considered). In one embodiment, the placement module **314** determines **622** whether there are any additional candidate slots among the one or more candidate slots.

Determining **616** whether the average flow control usage of the candidate device is greater in value than the average flow control usage of the incumbent device may include reading flow data from the expansion bus registers and comparing the average flow control usages for the candidate device and the incumbent device. Determining **616** whether the candidate device's average flow control usage is greater than that of the incumbent device ensures that the method **600** does not generate an arrangement with poorer throughput than the current arrangement.

In response to determining **616** that the candidate device's average flow control usage is greater than that of the incumbent device, the method **600** proceeds to assign **618** the selected candidate device to the selected candidate slot. In one embodiment, the placement module **314** assigns **618** the selected candidate device to the selected candidate slot. In response to the candidate slot being empty, the method **600** also assigns **618** the selected candidate device to the selected candidate slot. Otherwise, in response to determining **616** that the candidate devices average flow control usage is not greater than that of the incumbent device, the method **600** proceeds to determine **622** whether there are any additional candidate slots among the one or more candidate slots. In certain embodiments, the method **600** may assign **618** the selected candidate device to the selected candidate slot in response to the average flow control usage of the candidate device being equal to the average flow control usage of the incumbent device.

Assigning **618** the candidate device to the candidate slot includes assigning the incumbent device to the incumbent slot. While the assignment **618** of the candidate device to the candidate slot is intended as a permanent assignment, the incumbent device may only be temporarily assigned to the incumbent slot. For example, the incumbent device may be later evaluated to be permanently assigned to an expansion bus slot, either to the incumbent slot or to another expansion bus slot.

In response to assigning **618** the candidate device to the candidate slot, the method **600** indicates **620** that the selected candidate device and its assigned expansion bus slot are optimally arranged and determines **626** whether there are any additional candidate devices among the one or more candidate devices. In one embodiment, the placement module **314** indicates **620** that the selected candidate device and its assigned expansion bus slot are optimally arranged and determines **626** whether there are any additional candidate devices among the one or more candidate devices. In some embodiments, the flow control data module **102** maintains a data structure mapping candidate devices and candidate slots, and indicating **620** that the selected candidate device and its assigned expansion bus slot are optimally arranged includes mapping the selected candidate device to its assigned expansion bus slot and flagging the corresponding map entry as optimized. In certain embodiments, indicating **620** that the selected candidate device and its assigned expansion bus slot are optimally arranged prevents the assigned expansion bus slot from later becoming a candidate slot during calculating an arrangement of the plurality of expansion devices.

Determining **622** whether there are any additional candidate slots among the one or more candidate slots, in one embodiment, may include reviewing a list of candidate slots associated with the selected candidate device. In another embodiment, determining **622** whether there are any additional candidate slots among the one or more candidate slots may include indicating the (previously) selected candidate slot as having been considered, for example, by setting a flag or by removing the selected candidate slot from the list of candidate slots.

In response to determining **622** that there is at least one additional candidate slot, the method **600** selects **624** a candidate slot with a next highest flow control limit. In one embodiment, the placement module **314** selects **624** a can-

didate slot with a next highest flow control limit. Otherwise, in response to determining **622** that there are no more additional candidate slots, the method **600** determines **626** whether there are any additional candidate devices among the one or more candidate devices. In some embodiments, the selected candidate device and its current expansion slot may also be re-assigned to one another and/or be indicated as optimally arranged in response to determining **622** that there are no more additional candidate slots.

Selecting **624** the candidate slot with a next highest flow control limit, in one embodiment, may include accessing flow control limits for the remaining candidate devices. In another embodiment, selecting **624** the candidate slot with a next highest flow control limit may include selecting a remaining candidate slot where only one candidate slot remains to be considered. In response to selecting **624** the candidate slot with a next highest flow control limit, the method **600** again determines **614** whether both the newly selected candidate slot (e.g., the candidate slot with the next highest flow control limit) and the incumbent slot are physically capable of coupling to both the candidate device and an incumbent device (e.g., an expansion device coupled to the newly selected candidate slot).

Determining **626** whether there are any additional candidate devices among the one or more candidate devices, in one embodiment, may include reviewing a list of candidate devices and/or reviewing the mapping structure for expansion devices indicated as candidate devices. In a further embodiment, determining **626** whether there are any additional candidate devices among the one or more candidate devices may include indicating the (previously) selected candidate device as having been considered, for example, by removing a candidacy indication from the mapping structure or by removing the selected candidate device from the list of candidate devices.

In response to determining **626** that there is at least one additional candidate device, the method **600** selects **628** a candidate device with a next highest average flow control usage and again determining **610** candidate slots for the newly selected candidate device, each candidate slot having a flow control limit of greater value than the average flow control usage of the candidate device. Otherwise, in response to determining **626** that there are no more additional candidate devices, the method **600** ends. In some embodiments, the calculated arrangement of the plurality of expansion devices may be output in response to determining **626** that there are no more additional candidate devices.

FIGS. **7**A-**7**C are diagrams illustrating one embodiment of optimizing expansion devices on a computer expansion bus based on real-time flow control data, according to embodiments of the disclosure. FIG. **7**A depicts an expansion bus **700** in an initial state. The expansion bus **700** includes a first expansion bus slot **702**, a second expansion bus slot **704**, a third expansion bus slot **706**, and a fourth expansion bus slot **708**. Coupled to the expansion bus slot **702-708** are a first expansion device **710**, a second expansion device **712**, a third expansion device **714**, and a fourth expansion device **716**. Each expansion bus slots **702-708** are associated with a flow control limit, indicating a maximum number of flow control credits. In the depicted embodiment, the first expansion bus slot **702** has a flow control limit of 20, the second expansion bus slot **704** has a flow control limit of 50, the third expansion bus slot **706** has a flow control limit of 45, and the fourth expansion bus slot **708** has a flow control limit of 25.

A computer system including the expansion bus **700** is run for some duration allowing the expansion devices to use flow control credits. Flow control data is thus generated for each expansion device and stored, for example in a plurality of expansion bus registers. In one embodiment, a flow control data apparatus **200** and/or a flow control data apparatus **300** generates and stores the flow control data, as described above with reference to FIGS. **2** and **3**. The apparatuses **200**, **300** may be communicatively connected to the expansion bus **700**. For example, the expansion bus **700** may reside in the same computer system as the flow control data apparatus **200** or the flow control data apparatus **300**. In another embodiment, the flow control data apparatus **200** and/or flow control data apparatus **300** may be integrated with the expansion bus **700**.

As shown, each expansion device **710-716** has an average flow control usage, indicating an average number of flow control credits consumed during a particular period of time (e.g., during peak operation). In the depicted embodiment, the first expansion device **710** has an average flow control usage of 20, the second expansion device **712** has an average flow control usage of 45, the third expansion device **714** has an average flow control usage of 30, and the fourth expansion device **716** has an average flow control usage of 15. While the depicted embodiment optimizes the arrangement of expansion devices based on average flow control usage, in other embodiments other metrics may be used to optimize the arrangement of expansion devices, such as a ratio of average flow control usage to flow control limit for each expansion device, an average amount of available flow control credits for each expansion device, and/or a number of times the expansion device reaches the flow control limit.

Each expansion bus slot **702-708** has a physical size. Similarly, each expansion device **710-716** has a physical size. The expansion bus slots **702-708** may couple to expansion devices less than or equal to their physical size. As depicted, the first expansion bus slot **702**, the second expansion bus slot **704**, and the third expansion bus slot **706** are all physically sized for 16 lanes, while the fourth expansion bus slot **708** is physically sized for eight lanes. Also as depicted, the first expansion device **710** has eight lane connector, the second expansion device **712** has a sixteen lane connector, the third expansion device **714** has an eight lane connector, and the fourth expansion device **716** has a four lane connector.

FIG. **7**B depicts expansion bus **700** during a first step of optimizing expansion devices based on real-time flow control data. An optimizing device (not depicted), such as the flow control data module **102**, identifies which expansion devices **710-716** are at or near the flow control limit for its associated expansion bus slot **702-708**. In some embodiments, the optimizing device determines whether an expansion device **710-716** is within a predetermined percentage of the flow control limit of its associated expansion bus slot **702-708**. The expansion devices at or near the flow control limit become candidate devices. As depicted, the first expansion device **710** and the third expansion device **714** are candidates for rearrangement due to their average flow control usage being at the flow control limits of the first expansion bus slot **702** and the third expansion bus slot **706**, respectively. In certain embodiments, the optimizing device creates a list of the candidate devices.

The optimizing device identifies the candidate device having the highest average flow control usage. Here the third expansion device **714** has the highest average flow control usage (e.g., 45 vs. 20). Next, the optimizing device determines which other expansion bus slots **702**, **704**, and **708** have a greater flow control limit than the third expansion bus slot **706**. In this case, second expansion bus slot **704** has a

greater flow control limit than the third expansion bus slot **706** (e.g., 50 vs. 45). The optimizing device then determines whether the expansion bus slots **704** and **706** are physically compatible with both of the second expansion device **712** and the third expansion device **714**. Here, the optimizing device confirms that the expansion bus slot **704**, **706** are physically compatible with both of the expansion devices **712**, **714** as both expansion bus slots are physically sized for 16 lanes while neither expansion device is larger than 16 lanes. In certain embodiments, the optimizing device may further confirm that the expansion bus slots **704**, **706** include sufficient electrical connections for the expansion devices **712**, **714**.

The optimizing device next determines whether the second expansion device **712** is at the maximum flow control limit for its expansion bus slot (e.g., second expansion bus slot **704**) and whether the average flow control usage of the second expansion device **712** is greater than to the average flow control usage of the candidate device (e.g., the third expansion device **714**). Here, the answer is no for both determinations and the optimizing device assigns the third expansion device **714** to the second expansion bus slot **704**, as indicated by the arrow **718**. In certain embodiments, the optimizing device may provide instructions to a user that the second expansion device **712** and the third expansion device **714** should swap places on the expansion bus **700**.

FIG. **7**C depicts expansion bus **700** during a second step of optimizing expansion devices based on real-time flow control data. In some embodiments, the optimizing device marks the combination of the second expansion bus slot **704** and the third expansion device **714** as optimized, such that the third expansion device **714** cannot be reassigned from the second expansion bus slot **704**. The optimizing device identifies the first expansion device **710** as the candidate device having the next highest average flow control usage. In certain embodiments, the optimizing device also removes the third expansion device **714** from the list of candidate devices.

Next, the optimizing device determines which other expansion bus slots **706**, **708** have a greater flow control limit than the first expansion bus slot **702**. In this case, third expansion bus slot **706** has a greater flow control limit than the first expansion bus slot **702** (e.g., 45 vs. 20). The optimizing device then determines whether the expansion bus slots **702** and **706** are physically compatible with both of the first expansion device **710** and the second expansion device **712**. Here, the optimizing device confirms that the expansion bus slot **702**, **706** are physically compatible with both of the expansion devices **710**, **712** as both expansion bus slots are physically sized for 16 lanes while neither expansion device is larger than 16 lanes. In certain embodiments, the optimizing device may further confirm that the expansion bus slots **702**, **706** include sufficient electrical connections for the expansion devices **710**, **712**.

The optimizing device next determines whether the second expansion device **712** (e.g., the incumbent device) is at the maximum flow control limit for its expansion bus slot (e.g., third expansion bus slot **706**) and whether the average flow control usage of the second expansion device **712** is greater than to the average flow control usage of the candidate device (e.g., the first expansion device **710**). Here, while the second expansion device **712** is not at the flow control limit of the third expansion bus slot **706**, the second expansion device **712** has a greater average flow control usage than the first expansion device **710**. Accordingly, the optimizing device does not assign the first expansion device **710** to the third expansion bus slot **706** as this would result in a worse configuration than before due to the second expansion device **712** (having an average flow control usage of 30) being restricted by the flow control limit of the first expansion bus slot **702**.

Thus, the optimizing device searches for in other expansion bus slot having a greater flow control limit than the first expansion bus slot **702**. In this case, the fourth expansion bus slot **708** has a greater flow control limit than the first expansion bus slot **702** (e.g., 25 vs. 20). The optimizing device then determines whether the expansion bus slots **702** and **708** are physically compatible with both of the first expansion device **710** and the fourth expansion device **716**. Here, the optimizing device confirms that the expansion bus slot **702**, **708** are physically compatible with both of the expansion devices **710**, **716** as the fourth expansion this bus slot **708** is physically sized for eight lanes and neither expansion device requires more than eight lanes. In certain embodiments, the optimizing device may further confirm that the expansion bus slots **702**, **708** include sufficient electrical connections for the expansion devices **710**, **716**.

The optimizing device next determines whether the fourth expansion device **716** (e.g., the incumbent device) is at the maximum flow control limit for its expansion bus slot (e.g., fourth expansion bus slot **708**) and whether the average flow control usage of the fourth expansion device **716** is greater than to the average flow control usage of the candidate device (e.g., the first expansion device **710**). Here, the answer is no to both determinations. Accordingly, optimizing device assigns the first expansion device **710** to the fourth expansion bus slot **708**, as indicated by the arrow **720**. In certain embodiments, the optimizing device may provide instructions to a user that first expansion device **710** and the fourth expansion device **716** should swap places on the expansion bus **700**.

FIG. **7**D depicts a calculated arrangement **720** of the plurality of expansion devices **710**-**716** on the expansion bus **700**. The calculated arrangement **720** is the result of optimizing expansion devices based on real-time flow control data described above, for example in FIGS. **7**A-**7**C. As depicted, the fourth expansion device **716** is placed in the first expansion bus slot **702**, the second third expansion device **714** is placed in the second expansion bus slot **704**, the second expansion device **712** is placed in the third expansion bus slot **706**, and the first expansion device **710** is placed in the fourth expansion bus slot **708**. Calculated arrangement **720** maximizes throughput, based on flow control. In some embodiments, the computer system including the expansion bus **700** is run for an additional duration of time, and flow control data relating to the new arrangement of the expansion devices **710**-**716** is gathered. In further embodiments, the calculated arrangement **720** may be further evaluated based on the new flow control data to verify that the calculated arrangement **720** is an optimal arrangement.

While the embodiments depicted in FIGS. **7**A-**7**D show for expansion devices and for expansion bus slots, in other embodiments the expansion bus **700** may include more expansion devices and more expansion bus slots. Accordingly, where more expansion devices exist, the list of candidate devices may include more expansion devices and the optimizing device may iteratively assign each candidate device to an expansion bus slot, resulting in additional steps of optimizing expansion devices based on real-time flow control data.

Embodiments may be practiced in other specific forms. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of

the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

What is claimed is:

1. An apparatus comprising:

a configuration module that initializes a plurality of expansion bus registers, each expansion bus register associated with one of a plurality of expansion bus slots;

a packet module that monitors flow control packets on an expansion bus;

a flow control module that calculates, from the flow control packets, flow control data for each of a plurality of expansion devices operating on the expansion bus, each expansion device being received into one of the plurality of expansion bus slots, wherein the flow control module updates the flow control data as new flow control packets are received; and

a register module that writes the flow control data to a corresponding one of the plurality of expansion bus registers, wherein the register module updates the flow control data stored in the plurality of expansion bus registers as additional flow control data is received,

wherein said modules comprise one or more of a hardware circuit, a programmable hardware device, and a processor executing code.

2. The apparatus of claim **1**, further comprising an optimization module that calculates an arrangement of the plurality of expansion devices, based on the flow control data, to maximize expansion bus throughput.

3. The apparatus of claim **2**, further comprising:

a relocation module that prompts a user to relocate at least one of the plurality of expansion devices into a different expansion bus slot; and

a reset module that deletes data values stored in the plurality of expansion bus registers in response to the at least one expansion device being relocated, wherein the register module writes new flow control data to the plurality of expansion bus registers based on the relocated at least one expansion device.

4. The apparatus of claim **2**, wherein optimization module includes:

a slot limit module that identifies flow control limits for each of the plurality of expansion bus slots;

a candidate module that compares, for each of the plurality of expansion bus slots, an average flow control usage for an expansion device using the expansion bus slot to an identified flow control limit for the expansion bus slot, the flow control data including average flow control usage for each of the plurality of expansion devices, wherein the candidate module selects at least one candidate expansion device from the plurality of expansion devices based on the comparison; and

a placement module that assigns each candidate expansion device to one of the plurality of expansion bus slots based on the average flow control usage and the flow control limits.

5. The apparatus of claim **4**, further comprising:

a priority module that ranks the at least one candidate expansion device based on highest average flow control usage; and

a compatibility module that compares a physical size of an expansion device to a size supported by an expansion bus slot, wherein the placement module assigns each candidate expansion device to one of the plurality of expansion bus slots based on the size comparison.

6. The apparatus of claim **1**, wherein the configuration module further comprises:

an allocation module that identifies an unused expansion bus register for each expansion bus slot and allocates the unused expansion bus registers for storing the flow control data; and

a reset module that deletes data values stored in the allocated expansion bus registers.

7. The apparatus of claim **1**, wherein the plurality of expansion bus registers further comprises a plurality of extended capability registers for a peripheral component interconnect express (PCIe) expansion bus, each extended capability register storing the flow control data of one of plurality of expansion bus slots.

8. The apparatus of claim **1**, wherein the flow control data comprises one or more of: average flow control usage for each expansion device, a ratio of average flow control usage to flow control limit for each expansion device, and an average amount of unused flow control credits for each expansion device.

9. The apparatus of claim **1**, wherein the register module further updates the flow control data stored to the plurality of expansion bus registers in response to the flow control module calculating additional flow control data.

10. A method comprising:

initializing a plurality of expansion bus registers, each expansion bus register associated with one of a plurality of expansion bus slots;

monitoring for flow control packets on an expansion bus;

extracting, from the flow control packets, flow control data for each of a plurality of expansion devices operating on the expansion bus, each expansion device being received into one of the plurality of expansion bus slots, wherein extracting the flow control data comprises updating the flow control data as new flow control packets are received; and

writing the flow control data to a corresponding one of the plurality of expansion bus registers, wherein writing the flow control data comprises updating the flow control data stored in the plurality of expansion bus registers as additional flow control data is received.

11. The method of claim **10**, further comprising calculating an arrangement of the plurality of expansion devices that optimizes throughput based on the flow control data, wherein each of the plurality of expansion devices is coupled to one of the plurality of expansion bus slots.

12. The method of claim **11**, further comprising:

prompting a user to relocate at least one of the plurality of expansion devices into a different expansion bus slot based on the calculated arrangement of the plurality of expansion devices;

determining that the at least one expansion device is relocated;

resetting the plurality of expansion bus registers storing the flow control data; and

writing new flow control data to the plurality of expansion bus registers based on the relocated at least one expansion device.

13. The method of claim **11**, wherein optimizing throughput of the plurality of expansion devices based on the flow control data comprises:

identifying flow control limits for each of the plurality of expansion bus slots;

comparing, for each of the plurality of expansion bus slots, an average flow control usage for an expansion device using the expansion bus slot to an identified flow control limit for the expansion bus slot, the flow control

data including average flow control usage for each of the plurality of expansion devices;

determining at least one candidate expansion device from the plurality of expansion devices based on the comparison; and

assigning each candidate expansion device to one of the plurality of expansion bus slots based on the average flow control usage and the flow control limits.

14. The method of claim **13**, further comprising assigning a priority to each candidate expansion device based on average flow control usage, wherein a candidate expansion device having a highest average flow control usage is assigned a highest priority, wherein assigning each candidate expansion device to one of the plurality of expansion bus slots is further based on the priority of each candidate expansion device.

15. The method of claim **13**, wherein assigning each candidate expansion device to one of the plurality of expansion bus slots comprises:

selecting a candidate expansion device having a highest average flow control usage, the selected candidate expansion device being coupled to an incumbent expansion bus slot;

determining at least one candidate expansion bus slot from the plurality of expansion bus slots, each candidate expansion bus slot being physically compatible with the selected candidate expansion device and having a flow control limit larger than the average flow control usage of the selected candidate expansion device;

selecting a candidate expansion bus slot having a highest flow control limit, the selected candidate expansion bus being coupled to an incumbent expansion device;

determining that the incumbent expansion device is physically compatible with the incumbent expansion bus slot; and

determining that an average flow control usage of the incumbent expansion device is less than or equal to the average flow control usage of the candidate expansion device.

16. The method of claim **10**, wherein initializing the plurality of expansion bus registers further comprises allocating an extended capability register for each expansion bus slot for storing the flow control data.

17. The method of claim **10**, wherein initializing the plurality of expansion bus registers further comprises:

identifying an unused expansion bus register for each expansion bus slot;

allocating the identified registers for storing the flow control data; and

resetting data values stored in the allocated expansion bus registers.

18. The method of claim **10**, wherein extracting flow control data from the flow control packets comprises calculating a number of available flow control credits.

19. The method of claim **10**, wherein writing flow control data to the plurality of expansion bus registers comprises, for each of the plurality of expansion bus slots, storing an average flow control usage for an expansion device associated with the expansion bus slot.

20. A program product comprising a computer readable storage medium that is not a transitory signal and that stores code executable by a processor, the executable code comprising code to perform:

initializing a plurality of expansion bus registers, each expansion bus register associated with one of a plurality of expansion bus slots;

detecting flow control packets on an expansion bus;

calculating, from the flow control packets, flow control data for each of a plurality of expansion devices operating on the expansion bus, each expansion device being received into one of the plurality of expansion bus slots, wherein calculating the flow control data comprises updating the flow control data as new flow control packets are received;

storing the flow control data to a corresponding one of the plurality of expansion bus registers based on the flow control packets; and

updating the stored flow control data in the plurality of expansion bus registers as additional flow control data is received.

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